

Large-scale Quantum Communication Networks with Integrated Photonics

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)

Review of Nature ms 2024-10-21482

Dear Editor,

Please find below my review of Nature manuscript 2024-10-21482 entitled "Scaling Quantum Communication Networks with Microcomb-driven Integrated Photonics", by Professor Wang and co-authors. In this manuscript, the authors describe the experimental realization of a large-scale TF-QKD network based on integrated photonics. A central node hosting a micro-comb chip is used to distribute a highly coherent optical frequency comb lines for phase reference and centralized measurement-device independent detection. In the lab, it is understood that 20 remote nodes connected via long fibre spools up to 370km host fully integrated chips combining the functions of phase regeneration via optical injection locking, phase and intensity encoding of the quantum signal, and regeneration of a reference signal for stabilization. Each node receives one comb line for quantum state encoding and the central comb line for reference and phase evolution tracking. The authors present the results of their TF-QKD network measurements in the finite-size regime and show that the fundamental repeaterless bound is overcome across all 10 channels (10 different wavelengths) of the network. While the scalability and parallelism claimed in the manuscript would be an impressive tour de force, there is some ambiguity related to the experimental details and the exact scale of the experimental setup: it is unclear whether an actual network of client chips was implemented or if the experiment was repeated at 10 different wavelengths using the same pair of client chips. In addition, a few technical elements and choices need to be explained or justified. Before a decision can be made, the authors are therefore invited to clarify some details related to the experiment.

Experimental conditions

It is not clear whether the experiment ran with all channels in parallel and simultaneously, or whether the different sets of data were acquired sequentially.

On several occasions it is stated that the network spans 3700 km of fibre:

Abstract: "Our network parallels TF-QKDs between transmitter chips across twenty channels, with each paired QKD exceeding the repeaterless bound over a 370-kilometre spooled fibre, resulting in a total distance of 3700 kilometres."

Page 1, col. 2: "Our quantum network covers a total communication distance $NL/2$ exceeding 3700 km without any trusted relays, after 10 trillion cycles of communication tested."

Page 5: "The QKD client chips were symmetrically linked to the server via long fibres spanning up to 185 km, resulting in a maximum distance of $L = 370$ km between each user pair. The network comprises $N = 20$ channels, yielding a total communication distance of $NL = 3700$ km."

Caption of Fig. 5: "In the TF-QKD network presented in this work, we achieved a total communication distance of $NL/2 = 3700$ km, with $N = 20$ users and $L = 370$ km channel distance."

Page 7, col. 1: "Through the validation of bit transmission, the architecture and hardware have been proven capable of supporting many-channel networks accommodating 20 clients, spanning a total communication distance exceeding 3700

km, with each channel enabling the distribution of secure keys that surpass the repeaterless bound.”

Table S5 mentions “20 different paired TF-QKD users in the network”.

However, it seems that this is in fact a cumulated distance. It appears that there are only 2 fibre spools of 185km, one used to multiplex the A client chips, and another one use to multiplex the B client chips. To avoid leading the general reader into assuming that 3700km of spooled fibres were used in the experiment, the 3700km should be mentioned as a capability rather than a total distance. Terms like “spanning a total communication distance of 3700km” are very misleading to the general readership.

Likewise, there are not $N = 20$ independent channels. There are 10 wavelengths traveling into the same fibre. This makes at most 10 effective channels. In this statement the authors seem to have made a confusion between the number of clients (defined as N) and the number of channels. The intention of the authors to consider each wavelength as a distinct channel is understandable, however the problem is again that the statement may be misleading. The experimental conditions are not clearly stated in the abstract, introduction or conclusion. The figures, abstract and comments refer to the perspective and concept of a deployed TF-QKD network rather than an actual TF-QKD network proof-of-concept experiment, and this is misleading to the reader. Table S5 also mentions 20 different paired clients instead of 20 different settings.

The microcomb source is stated as the heart of this work. I agree that it is a milestone to apply this source to TF-QKD, however such sources are not new and have been studied extensively in the literature. In contrast, a more impressive achievement would be the demonstration of high scalability through the fabrication and operation of 20 nearly identical client chips, and their parallel operation, provided that the authors confirm this in the previous question.

It is unexpected that only little data is given regarding the 20 independent client chips.

This level of scalability and parallelism with InP chips, if confirmed by the authors, is a significant advance for chip-based quantum communication applications, however no fabrication detail is given regarding these chips. No information about yield, reproducibility, etc., that would help the reader appreciate the work to its full extent.

A natural dataset to show would be a plot of the optical spectra of the 20 independent lasers showing the 20 central wavelengths before tuning, after tuning to the ITU channels, and after seeding by the microcomb lines should be presented for all chips or included in the supplementary information.

Another significant ambiguity relates to the actual number of independent chips in the TF-QKD network experiment. Can the authors please confirm how many independent client chips were used in total? It is suggested that 20 client chips (10xA chips and 10xB chips) were used in the TF-QKD network experiment, each aligned to a different comb line, however the number of client chips is not stated unambiguously. This would help the reader appreciating the scalability of the photonic integration technology used in this work. In relation to this question, how similar/dissimilar are the building blocks on the different chips (laser central wavelengths, intensity modulator ERs, phase modulators Vpi, etc).

It is not clear whether the phase tracking done in parallel for all channels, or sequentially, pair by pair. If the channels are multiplexed in the same fibre, how was the phase stabilization done in parallel? How many independent phase modulators and SNSPD channels are used to stabilize the reference central comb line, λ_0 ?

Technical aspects and protocol implementation:

In the experiment, a short fibre is used between the server and client nodes: what is the power of each comb line after filtering? Is the choice of a short servo fibre motivated by technical limitations? For example, for a 185 km servo fibre, the EDFA would need to compensate for nearly 40 dB loss: is it feasible to amplify the combs lines sufficiently without introducing too much ASE and degrade the OIL performance? Would the experiment still work with 185 km of fibre between the microcomb and the client chips, and if not, what would be the limitation?

The comb lines are split by 30.03 GHz, but this doesn't align with ITU channels as opposed to what is stated in the introduction. Which ITU channels were used for each pair of clients and how did the authors mitigate deviations from the ITU grid?

How critical is the temperature stabilization of the micro-ring chip and how does the comb-line drift over time? Is the microcomb chip only stabilized by temperature? Is it locked to the HCN cell? If not, how stable is it in time?

There is no mention of the number of added phases used at Alice (Bob) for key encoding and phase randomization. Can the authors describe how this was implemented?

The quantum bit error rates in the Z and X bases are not given, nor discussed. Can the authors report these values in a table?

Long fibres tend to expand with temperature, causing fluctuations in the time of flight that can reach hundreds of ps. Did the authors observe photon arrival time drifts over the long fibre links and how was that addressed for the different client pairs?

Other:

In the literature review, the authors include prior work related to chip-based MDI-QKD, however they seem to have missed a more recent work on chip-based TF-QKD, also implementing optical injection locking and phase encoding on chip. This

reference should be added for completeness.

Page 6: "Infinite-size effects" should be rephrased "finite-size effects".

Table S5 isn't mentioned in the main text or supplementary material.

Referee #2

(Remarks to the Author)

In their paper, Zheng et al. reports a very nice demonstration of the possibility of using a microcomb-driven integrated photonic QKD network that exploits Twin Field QKD, a technology that allows, in principle, to increase the distance of key transmission at a reasonable rate.

While the proposed article is undoubtedly of high impact for the quantum communication community, I do not believe it holds the same level of significance for a broader audience. The existence of star networks for QKD is not a novelty, the Twin Field protocol is well known, and the dual-band system for phase noise stabilization in optical fibers has already been widely demonstrated so this paper brilliantly overcomes the technological challenge of stabilizing multiple Twin Field setups simultaneously. However, in itself, I do not believe a general audience would appreciate this technological advancement as much as a more specialized readership would. Moreover, the paper is written in a rather technical way which makes it unsuitable for a wide audience.

For this reason, I don't recommend the publication in Nature but the resubmission to a more specialistic journal.

Anyway, there are some points that, in my opinion, authors should consider improving the presentation of their results, in the case of a new submission:

1. The core of the paper is the use of microcombs to allow simultaneous phase tracking by using dual band method in each channel of the network. Anyway, they state that they use postselection instead of phase shift compensation. I'm a rather bit confused: why authors are using a method that is born to stabilize the channel and avoid postselection of data if they do perform postselection? The authors should better explain this point
2. In general, the description of the implementation of dual-lambda method is poor. They refer to paragraph 3.2 of the supplementary materials which is extremely synthetic. I suggest they better explain how they perform this operation in particular highlighting, for example, how the frequency and phase noise on the channel can be influenced by the noise of the microcomb or how the fluctuation of the residual phase noise could affect the QBER.
3. Then, a comment by the authors on the characteristic time scales of the measurement could be useful to connect the information provided in figures 2(f-k) to those in figure 2(m).
4. TF-QKD is a protocol useful for long distance QKD. Why the authors decided to use an optical link of 102 km + 102 km, where Twin-Field QKD doesn't overcome the PLOB bound?
5. The text provides extensive details on microcombs but lacks sufficient information on the single-photon aspects, such as the specifications of the single-photon detectors and the residual background photons resulting from the dual-band technique. In the discussion section, the authors suggest that using SNSPDs can enhance the performance of their approach. However, if I understand correctly, SNSPDs were already used in this experiment. Overall, the authors should improve the clarity and effectiveness of their description of key technical aspects, ensuring a better understanding of the reliability and advantages of the Twin-Field transmission.
6. To improve the article, the authors could give some additional details regarding the metrological characterization of the microcomb. In fact some information can be intuited from the caption of figure 2, but in the article they are barely mentioned. So I suggest to address the metrological part by adding this information in the supplementary materials. In particular, I suggest to better explain in the text what the authors mean by synchronization and stabilization.
7. In Fig. 2 "(g), Characterisation of spectral stability of microcombs, collected every minute over 12 hours." I suggest explicating in which way they perform this measure. This is important to understand also the statement related to fig.2 (h) and (i) "(h), microcomb seeding lasers at the server, and (i), synchronised slave lasers on the QKD client chips". Unfortunately, much of the information needed for a better understanding of the work is written in a rather cryptic manner in the text.
8. Authors declare "Microcombs with Hz-level linewidths" in fig.2 and in the text. In particular "(j), Summary of measured intrinsic linewidths for comb lines in the microcomb and synchronised slave lasers, showing narrow average linewidths of 85.6 Hz and 96.9 Hz, respectively. Points are experimental data and lines are their mean values. (k), Measured beatnote spectrum of the comb lines." It is not clear from the text how these measures have been realized. In particular, I suggest to explicate (in the text or in the supplementary materials) the statement of fig 2(k). The beat is between the comb line and what reference..?
9. I suggest to the authors to add a short sentence to explain the double peak of fig.2 (d)
10. In the supplementary information, authors describe the fabrication and calibration of the microresonator. In particular, they implement a calibration of the comb spectrum by using an HCN cell. I suggest to provide more details about this operation (cell pressure, cell geometry, etc.).

Referee #3

(Remarks to the Author)

In this work, the authors experimentally realized a proof-of-principle demonstration of a multi-user twin-field Quantum Key Distribution network. This network is enabled by a single optical frequency comb at the server side and multiple Indium

Phosphide integrated transmitters at the user locations, all optically locked to the central frequency comb.

In particular, the authors exploit an integrated Silicon Nitride microresonator, pumped by a DFB laser, to generate highly coherent and narrow optical frequency comb lines. These comb lines exhibit approximately 90Hz short-term linewidths and span a broad spectrum of frequencies in the C-band, with approximately 30 GHz spacing between comb lines. These comb lines, generated at the central server station, are then distributed to multiple user transmitters. At each user-side transmitter, two selected comb lines are used to optically lock DBR lasers integrated on the InP PICs via optical injection locking. One comb line acts as a phase reference for the dual-lambda stabilization, while the other serves as the seed for the quantum signal. This quantum signal is then prepared and encoded on-chip for each user. The PICs include three intensity modulators and one phase modulator, used for time-bin encoding, decoy preparation, and phase randomization. In this wavelength-multiplexed configuration, each user pair utilizes a dedicated wavelength channel, resulting in $N/2$ independent pairwise TF-QKD links for N users. Finally, the encoded quantum states from each user are transmitted back to the central station via fiber spools, where they are interfered and measured using SNSPDs. The authors successfully demonstrated positive Secure Key Rates (SKR) for spooled fiber links up to 370 km, achieving key rates that surpass the PLOB bound with ten user pairs.

The work is original and presents a significant advancement in the field of quantum communication. The innovative use of a single optical frequency comb, coupled with a multitude of integrated photonic chips, including lasers and modulators, is a significant demonstration of the potential to develop mass-manufacturable and scalable QKD networks, even for advanced protocols like TF-QKD.

The manuscript is clearly written, with some points (presented below) which can be improved. The methodology and data analysis is generally sound, although some parts need to be clarified.

The use of uncertainties is generally correct, although some measured quantities are missing the relative uncertainty. As an example the measured D1, D2 and D3 are missing the uncertainties as well as table S3.

Regarding the manuscript, I have the following comments:

- In both the abstract and in the introduction, the use of the term "photonic QKD network," combined with the intrinsic star topology of the network, may confuse the reader into thinking that full mesh connectivity between the different users has been shown, while in the experiment only pairwise links have been realized thanks to wavelength multiplexing. For the sake of clarity, I suggest that the authors better clarify this point.
- In the introduction, the authors briefly mention that frequency shifting would be "required for those users with different wavelengths." To enhance the completeness of the work, it would be beneficial if the authors could elaborate further on this aspect. Specifically, could they provide more detail on how frequency shifting would be implemented in this network architecture, and perhaps discuss any potential penalties, such as increased losses, associated with this frequency shifting process?
- Regarding the spectral stability of the comb, this has been measured for 12 hours and shown in Fig 2g. However, from the figure, it is difficult to appreciate such stability. Can the authors also add a numerical estimate of this stability?
- In the implementation of the decoy state protocol with weak coherent pulses, achieving robust phase randomization is crucial. The manuscript mentions using a single phase modulator for active phase randomization. To provide a more complete picture of the experimental implementation and security analysis, it would be helpful if the authors could clarify a few points regarding phase randomization. Could the authors specify the number of discrete phase levels used for the active phase randomization in their setup? Was the achieved level of phase randomization experimentally characterized or measured? To ensure a comprehensive security analysis, was the potential impact of any imperfect (i.e., discrete rather than continuous) phase randomization considered in the Secure Key Rate (SKR) calculations? If so, could the authors elaborate on how this was accounted for and the magnitude of its effect, if any, on the reported secure key rates?
- A potentially critical aspect of the experimental setup is the significant difference in length between the downstream fibers used for comb distribution and the upstream quantum communication links. While understandable for a lab demonstration, this asymmetry raises questions about the representativeness of the results for a truly scalable, long-distance network. Specifically, the drastically shorter downstream fibers likely minimize several noise contributions that would become prominent in a deployment with comparable downstream and upstream distances. For instance, what impact would be observed if the downstream channels were also extended to lengths comparable to the upstream links? One could anticipate several potential downsides, such as increased phase noise accumulated along the longer downstream fiber paths, potentially impacting the phase locking stability at the client chips. Another point would be related to higher levels of Raman and scattering noise introduced in the extended downstream fibers, and additional noise due to the increased amplification demands on EDFAs for longer downstream comb delivery. While acknowledging the complexity of implementing fully symmetric fiber lengths across all links, it would significantly strengthen the demonstration to provide evidence, even for a single user pair, of successful operation with comparable downstream and upstream fiber distances.
- Regarding synchronization, it is not clear to me whether this is achieved optically with the disseminated comb lines or using external RF signals. From the main text, it appears that the comb lines are also used for synchronization; however, in the supplementary figure (S3), synchronization looks like it is performed using RF cables. Is this the case? What would be the impact of also performing the synchronization using the downstream/upstream link? This point would be required for a

real in-field implementation.

- I am wondering if the distribution of the comb lines from Charlie to the users can open side-channel attacks, such as wavelength shift attacks or trojan horse attacks. Could the authors comment on this point?
- From my understanding, the phase tracking with the comb lines works well if the two channels between Alice-Charlie and Bob-Charlie are symmetric; however, asymmetries in the channel, due to the finite frequency and phase stability, can degrade the phase tracking. Can the authors comment more on this point? If this is a problem for asymmetric channels, how can it be solved?
- It is not completely clear to me if the 10 pairs of links are performed in parallel at the same time with sharing of some common fiber, or are independently and sequentially performed. Can the authors clarify this point?
- Are the RF signals prepared from the AWG for the encoding in the QKD transmitters random sequences or fixed repeated sequences? If the latter, what is the length of the sequence?
- Is the post-processing part of the protocol performed in real-time or offline after the quantum phase ended?
- If the post-processing is performed offline and the signals from the AWG are made of repeated sequences, I suggest referring to the experiment as a proof-of-principle QKD experiment in the main text.

Some additional minor points:

- In the section "Demonstration of microcomb-driven integrated TF-QKD network," the authors write: "The infinite-size effect has been taken into account by sending a total of 10^{12} bins in each case. Moreover, we obtained the secure key rates at the two different communica..." I guess "infinite" is a typo for "finite."
- In equation S17, I suggest having the symbol f_{EC} in the formula for the error correction efficiency and keeping the value of 1.1 described in the text.

In conclusion, based on my previous comments, I currently cannot recommend the publication of the manuscript in Nature.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)

Review of Nature ms 2024-10-21482B

Dear Editor,

Please find below the review of the revised Nature Manuscript ID: 2024-10-21482 entitled "Large-scale Quantum Communication Networks with Integrated Photonics", by Professor Wang and co-authors. I have carefully read and considered the author's detailed and comprehensive response to the comment raised by all reviewers. I am pleased to read that in their response and revised manuscript, the authors report a profound improvement of the original experiment. Specifically, the first manuscript featured an ambiguity regarding the actual scale of the experiment. While it was suggested that the TF QKD experiment was performed using 10 independent pairs of client chips in parallel, there were a few indications that only 2 client chips were used and therefore several claims related to scalability and massive parallelism could not be justified.

The authors acknowledge that "In the first submitted version: the TF QKD network was implemented with two InP QKD client chips and 10 different wavelength channels determined by the microcomb lines."

Therefore, they propose a new experiment:

"In the revised version: the TF QKD network is now completely reimplemented using 20 independent TFQKD transmitter chips (...) and they are now simultaneously deployed. The TF QKD network between 20 client chips is centralised with a microcomb laser, which provides all chip-level resources required for parallel and simultaneous 20-user QKDs in the network."

The new experiment convincingly demonstrates the scalability claimed originally. The authors provide comprehensive and extensive characterization measurements of 20 InP client chips, which demonstrate high level of reproducibility and consistent high performance across all devices, reaching ultra-low linewidths under optical injection locking from a microcomb device and achieving TF-QKD secure key rate above the PLOB bound over 10 independent links.

Parallelism could not be fully demonstrated due to resource limitation. The authors explain that it is nevertheless emulated by measuring TF-QKD on client pairs sequentially while keeping the other links continuously active, which is acceptable for a proof-of-principle.

The revised manuscript is a substantial improvement of the experiment scale, and I acknowledge the authors' efforts and time in addressing all comments made during the first review. The high-quality cross-disciplinary results are expected to impact a broad readership from diverse background. I'm inclined to recommend publication of this work, however, this is pending carefully addressing the comments below, which I hope will help enhancing the accessibility to the general reader,

lifting all risks of experimental misinterpretation, and meeting the expectations of the expert reader.

1. Readability: the revised manuscript is very technical in its present form and may not directly be suitable for a general readership. There is indeed a challenge in finding the right balance between describing the extensive characterization dataset, describing the TF-QKD experimental conditions and performance, and a discussing the relevance and perspectives of this work for a practical, real-field implementation of TF-QKD networks. A suggestion would be that the authors consider focusing more on the latter than the former by moving some of the characterization measurements to the extended data section (or supplementary information) and including more of the discussion on the feasibility of a practical TF-QKD WDM network in the main text. In my opinion, this would make the manuscript more accessible to a broad readership, while still satisfying the experts expectations:

a. Fig. 2 could be split or be made more compact. Fig 2d and e are redundant. Fig 2j is not easy to appreciate, a plot of the max extinction ratio per IM would be quicker to understand. 2j and 2k could be moved to a SI section.

b. Statements such as “While this is currently a lab-scale demonstration, our integrated quantum photonic devices and technologies can be readily extended to field-deployable QKD networks” should be supported in the main text, as they immediately raise questions on stabilization and security. Therefore, the discussions of SI Section 5 (Towards real-field implementation of integrated-photonic TF-QKD networks – in particular considerations on channel asymmetry) and Section 6 (Security analysis – in particular security of OIL for TF-QKD) should if possible be summarized in the main text.

2. Packaging:

a. Each package features 2 chips with optical I/O on both sides, which might be challenging to manage. Out of curiosity, how many fibres are used per chip and is packaging done using fibre arrays or individual fibres? Do the authors have an estimation of the fibre coupling losses?

b. Are both chips of the same client pair assembled on the same package or are both clients of the same pair on physically separated nodes?

c. When the authors mention “simultaneously deployed”, how many clients are connected to the sever node at any point in time? It is understood that light from the server microcomb is split into 20 downstream fibres simultaneously. How much power reaches each client in the case of short and long downstream fibres?

3. Downstream link and WDM. It is mentioned that “for the {A5, B5} chips 120 km (60 km + 60 km) fibres were used to characterise the network with realistic long downstream fibres”. Is that:

a. 120 km in total for each downstream fibre as suggested by the caption of Fig 3f,3g “predominantly short downstream links, except for the {A5, B5} paired QKD which adopted 120 km downstream fibres”

b. 60 km for A5 and 60km for B5, with both comb lines in each fibre? In this case:

i. The authors should clarify in the caption that the phase drift is measured after propagation in a 60 km long fibre.

ii. The authors should comment on the feasibility of tracking the accelerated phase shift over fibres that are 3 times longer. From Fig 3d [A5,B5], ϕ_d seems to drift significantly faster than with short downstream fibres, so it's not clear whether the same postprocessing approach would still be able to cope with 185 km downstream fibre per client.

4. Wavelength division demultiplexing. Looking at Fig. 1, Fig. S3, and the comment it is difficult to understand where and how the demultiplexing of the reference and OIL comb lines is done.

a. Section ‘Architecture of the TF-QKD network’ proposes: “Microcomb lines are dispersed across the network via the backbone fibres and wavelength-demultiplexed at intermediate nodes before reaching the client-side chips.”

i. Is this precisely what is done in the experiment or is this a vision for a TF-QKD network implementation?

ii. In Fig S3, wave shaper II is used to send the reference and quantum lines to a specific client pair, but it is not clear what happens to the other microcomb lines and the other downstream fibres.

b. Fig. 3 caption: “while maintaining continuous operation of all other wavelengths multiplexed in the same fibres”. This suggests that the client is aligned to the microcomb line of interest for OIL without the need of filtering the other lines.

c. At the same time, page 4 explains “with each client-chip receiving two microcomb lines as seeds to implement the dual- λ phase tracking [18]” which seems to contradict the statement in Figure 3. Where in the links are the wavelengths demultiplexed? Which wavelength is sent to which node?

5. The mean photon number in the Z basis is greater than 0.5. It would be useful that the author comment on this choice, as it might affect the protocol security by increasing the risk of multi-photon events.

6. An important point of concern is the phase randomization/encoding approach. The authors should clarify how the phases between Alice and Bob are randomized with respect to one another while all the electronic signals are synchronized. The current explanation is that a sawtooth pattern is applied to the PM during 15 ms of quantum communication while the IM is carving pulses at 200 MHz, yielding 3 million different phases.

a. Why not encode a random pattern on each PM? It's expected that the PM RF bandwidth is high enough for that. What is the limitation?

b. Are the sawtooth patterns applied to PM 1 generated with the same frequency for both clients of a pair A_i, B_i ?

c. In SI 4.2, it is stated that: “For a proof-of-principle experiment, the preset repeated phase sequence effectively emulates the random phase settings [74]. The random phase and the encoding phase always work as a whole. We can consider the sawtooth voltage as providing phase randomisation and encoding phase at the same time, which would not affect the result while simplifying the implementation.” This seems to mean that the authors consider the sawtooth pattern as being random and encoded phase at the same time, however it doesn't explain how different phases are sent from both clients for a given X event.

d. This question is important because in a situation where all X basis events are matched in phase (i.e. always falling in the same phase slice, hence aligned in encoded and randomized phase), two issues could invalidate the SKR estimation, and the violation of the PLOB bound, even for a proof-of-principle experiment:

i. A situation with encoded phases being always well aligned with each other would increase $N_{\Delta} \pm$ (see Eq S16, S20) which may lead to a strongly underestimated phase QBER, in turn yielding an overestimated SKR.

ii. The number of X detections required to bound the phase QBER could be smaller than in a real-case scenario, so the finite size analysis, as presented, could also yield an overestimated SKR.

e. One could imagine that the fibre drift is used to decorrelate the phases, but as shown in 2e, due to the very high quality

and coherence of the microcomb, the phase drifts of the reference and quantum line are strongly correlated and the resulting phase difference barely drifts within the 15 ms of quantum communication, so the phases of both clients would always be in the same slice.

f. The authors may have implemented X events that are not correlated in phase, but it is not clear how, from the current description. This should be clarified to the readers, especially those familiar with TF-QKD. A plot of the distribution of $[(\delta_A - \delta_B) - (\phi_B - \phi_A)]$ after postprocessing would be helpful.

7. Security analysis. The authors do not mention any noise rejection routine. In existing implementations of the TF-QKD SNS protocol, two-way classical communication routines such as active odd-parity pairing (AOPP) are used to reduce the bit flip error rate and reach positive SKR. The secure key rate equation is very different from eq. S17. Notable examples where AOPP is used include the 1000-km TF-QKD experiment, where SNSPDs with dark count rates 0.014 Hz and 0.026 Hz were employed [Ref 20], and the TF-QKD without frequency dissemination work [Ref 21], where ultra-stable lasers are employed together with 1 Hz dark count SNSPDs and a field trial [Ref. 22]. Without AOPP, the reported Z QBER (E_z) can easily exceed 25 dB. It is therefore surprising not to see any mention of noise rejection routine in the manuscript.

a. An explanation may come from the combination of high extinction ratio (ER) between Send (S) and No-send (NS) states and low sending probability. In Ref 47, Fig.7 indicates that for $ER > 40$ dB, E_z becomes close to P_s . In the present work, the S/NS ER isn't given, but is expected to be high since E_z matches $P_s = 2.4\%$ at 204 km.

b. May the authors confirm the S/NS ER in their work? A minimum ER of 60 dB is reported between phase estimation and quantum communication period, using both IM2 and IM 3, while average individual IM ER is reported to be 33 dB. What is the S/NS ER during the quantum communication period?

c. A low P_s may reduce the rate of successful Z events. Therefore, P_s is generally adjusted as a function of the distance. How did the authors optimize their parameters (P_s , flux, probabilities)?

d. In any case, overcoming the PLOB without the need of noise rejection routine, is an interesting result that should be explicitly highlighted and commented in the text as an advantage coming from using photonic integrated circuits.

8. Two-client chips data. Although the first experiment didn't meet the criteria of scalability or parallelism, it is still of relevance as it demonstrates wavelength tunability, which is an important feature to enable network reconfigurability. The data have now been moved to the SI (Fig S8 and Table S6), however there is no mention of the experiment neither in the main text nor in the SI sections. The frequency shifter approach is interesting, however wavelength tunability should be also listed as a potential way to connect different clients for a fully connected network.

9. How much channel asymmetry can be tolerated with the 60 Hz linewidth?

10. A recent publication demonstrated a microcomb chip to implement WDM MDI-QKD network [Yan W. et al. npj Quantum Inf 11, 97 (2025)]. Although the microcomb lines are much broader than in the present work, a brief mention might be useful to include in the literature review.

11. Caption 2j, 2k: the measurements refer to the output intensity of the IMs not the EOPMs.

Referee #2

(Remarks to the Author)

Reading the new version of the paper and the very detailed reply to all the referees, we are really impressed by the amount of new experimental realizations and data acquired in so few weeks by Zheng et al. They have reimplemented the whole TF-QKD network, including twenty TF-QKD chips and have recollected all experimental data. The realization of pairwise QKD across twenty client-chips through ten wavelength-multiplexed channels, together with the clarification of some ambiguous details in the main and in supplementary sections, made this paper a very high level technical paper that bring significant advancement in the field of quantum communication.

Even if at proof-of-principle level, it represents for sure a technical advancement towards TF-QKD implementation, approaching a real scenario, where a scalable TF-QKD network could be achieved. As pointed out by the authors in their reply, the use of integrated quantum photonics and chip-scale miniaturization represents a fundamental step for a cost-effective scalable WDM TF-QKD architecture.

Since the results obtained by the authors, although remarkable, are still, in our opinion, too technical and specialistic for a journal as Nature, publication in a journal such as Nature Photonics or Nature Physics would place the paper within the appropriate reference community without in any way diminishing its scientific value.

Referee #3

(Remarks to the Author)

To the Authors,

Thank you for the extensive and impressive revisions to the manuscript and for your detailed response letter. The re-implementation of the experiment with 20 physical QKD chips and the inclusion of tests with symmetric long-haul fibers have substantially strengthened the work and addressed many of my initial concerns.

While the manuscript is much improved, I believe further clarification on a few points related to manufacturability and system-level scalability would significantly enhance the impact of your claims.

1. Overall Yield and Selection of Client-Side InP Chips:

The reported 97.5% yield for the electro-optic modulators is a strong indicator of the fabrication quality. However, this is a metric for a single component type. The overall yield of a fully functional QKD transmitter chip—where all lasers, modulators, and attenuators must work to specification—is a more critical metric for assessing mass-manufacturability.

Could you please clarify the wafer-level yield of fully operational InP QKD chips that passed all performance criteria? To provide context, could you state whether the 20 chips used in the experiment represent the total number of chips fabricated,

or if they were selected from a larger pool after other devices were discarded due to performance issues?

2. Scalability of the Server-Side Si₃N₄ Microcomb Fabrication:

The manuscript highlights that the scalable InP client chips were fabricated at a commercial foundry (Smart Photonics), which strongly supports claims of reproducibility. In contrast, the "Authors Contributions" section and supplementary details suggest the critical server-side Si₃N₄ microcomb was fabricated in-house at the university. This distinction is important for evaluating the end-to-end scalability of the network architecture.

Could you please comment on the scalability and reproducibility of this in-house Si₃N₄ fabrication process? Is the manufacturing of the microcomb itself a potential bottleneck for the large-scale deployment of this network architecture, and how does its fabrication yield and performance uniformity compare to the commercial foundry process used for the client chips?

Addressing these points would provide a more complete picture of the practical path toward large-scale deployment, directly supporting the manuscript's central theme of scalability.

Referee #4

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

Version 2:

Reviewer comments:

Referee #1

(Remarks to the Author)

Please find below the review of the revised Nature Manuscript ID: 2024-10-21482 entitled "Large scale Quantum Communication Networks with Integrated Photonics", by Professor Wang and coauthors. I have now reviewed the comprehensive response of the authors and the new manuscript. I am pleased to see that, in their response and the new manuscript version, the authors have lifted all risks of experimental misinterpretation and significantly improved the readability of the manuscript:

- The wafer-scale reproducibility for TF-QKD chips and their reliability in terms of fabrication and performance is a strong message which is now highlighted in the abstract and introduction. The conclusion was improved by the addition of fair considerations on potential limitations of the experimental conditions and prospect of practical deployment.
- The organization of new Figure 2 significantly improved clarity and accessibility.
- Likewise, SI 4.1 and Figure S5 now lift critical ambiguities and clearly demonstrate the scalability of the experimental setup.
- An important comment was raised regarding the phase encoding, namely the risk that the encoded X-basis state may have been matched in phase. The authors have now fully addressed this concern in SI 4.2. and Figure S7. SI 4.6 further describes the authors efforts in minimizing sources of noise and errors to consistently overcome the PLOB without the need of additional noise rejection routine.

I believe that, in its present shape, the manuscript will meet the expectations of expert readers while maintaining a sufficiently accessible message to reach a broad readership. The scalability achieved for such a challenging experiment, and the extensive set of data presented in the manuscript and supplementary material, are likely to strongly impact both the photonic integration and the quantum communications communities. I am therefore pleased to recommend publication of the manuscript in Nature, and I take the opportunity to congratulate the authors for their considerable work and efforts.

Referee #3

(Remarks to the Author)

The authors have satisfactorily addressed all my previous concerns and comments. The manuscript has been improved significantly and I believe it is now ready for publication. Therefore, I can recommend the publication in Nature.

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Referee #1 (Remarks to the Author):

Please find below my review of Nature manuscript 2024-10-21482 entitled "Scaling Quantum Communication Networks with Microcomb-driven Integrated Photonics", by Professor Wang and co-authors. In this manuscript, the authors describe the experimental realization of a large-scale TF-QKD network based on integrated photonics. A central node hosting a micro-comb chip is used to distribute a highly coherent optical frequency comb lines for phase reference and centralized measurement-device independent detection. In the lab, it is understood that 20 remote nodes connected via long fibre spools up to 370km host fully integrated chips combining the functions of phase regeneration via optical injection locking, phase and intensity encoding of the quantum signal, and regeneration of a reference signal for stabilization. Each node receives one comb line for quantum state encoding and the central comb line for reference and phase evolution tracking. The authors present the results of their TF-QKD network measurements in the finite-size regime and show that the fundamental repeaterless bound is overcome across all 10 channels (10 different wavelengths) of the network.

While the scalability and parallelism claimed in the manuscript would be an impressive tour de force, there is some ambiguity related to the experimental details and the exact scale of the experimental setup: it is unclear whether an actual network of client chips was implemented or if the experiment was repeated at 10 different wavelengths using the same pair of client chips. In addition, a few technical elements and choices need to be explained or justified. Before a decision can be made, the authors are therefore invited to clarify some details related to the experiment.

We are deeply grateful to the referee for their time, expertise, and thoughtful review of our manuscript. Their insightful and constructive comments have been invaluable in improving our work. In the revised manuscript, we have now carefully addressed all the referee's comments and suggestions. We particularly appreciate the referee's highly constructive feedback regarding the significance of clarifying the number of QKD transmitter chips implemented in the network and to further verify the scalability of InP QKD client chips, and the suggestion to characterise a more balanced QKD system with long downstream and upstream fibres. We have provided a detailed clarification in our response letter and revised the manuscript accordingly.

To address these points experimentally, we have reimplemented the entire TF-QKD network using **20 real TF-QKD chips** (see revised Fig. 1c) and have recollected nearly **all experimental data** in Fig.2, Fig.3, and Fig.4 of the main text, Extended Data Fig.1, along with additional supporting data in the Supplementary Information. We have reimplemented paired TF-QKD between two InP chips with long downstream and upstream fibres, and results have also been included in Fig.3 and Fig.4.

We sincerely believe that the referee's suggestions and comments have greatly enhanced the clarity and rigour of our manuscript, and we are thankful for the opportunity to strengthen our work.

Experimental conditions

It is not clear whether the experiment ran with all channels in parallel and simultaneously, or whether the different sets of data were acquired sequentially.

【We comprehensively address all of the referee's comments regarding: (1) the exact number of independent InP QKD client chips employed in our experiments, and (2) the reproducibility and performance variations among these InP QKD client chips. Note that the following comments from the referee have been consolidated here for a unified response to the referee's major comments.】

The microcomb source is stated as the heart of this work. I agree that it is a milestone to apply this source to TF-QKD, however such sources are not new and have been studied extensively in the literature. In contrast, a more impressive achievement would be the demonstration of high scalability through the fabrication and operation of 20 nearly identical client chips, and their parallel operation, provided that the authors confirm this in the previous question.

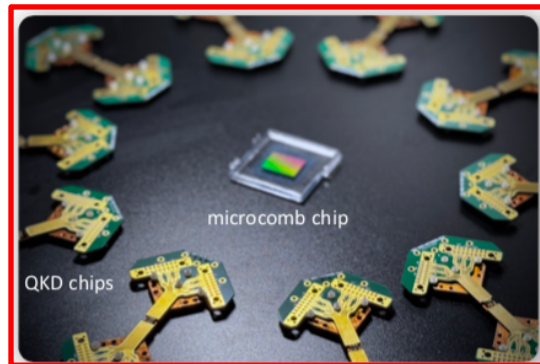
It is unexpected that only little data is given regarding the 20 independent client chips. This level of scalability and parallelism with InP chips, if confirmed by the authors, is a significant advance for chip-based quantum communication applications, however no fabrication detail is given regarding these chips. No information about yield, reproducibility, etc., that would help the reader appreciate the work to its full extent. A natural dataset to show would be a plot of the optical spectra of the 20 independent lasers showing the 20 central wavelengths before tuning, after tuning to the ITU channels, and after seeding by the microcomb lines should be presented for all chips or included in the supplementary information.

Another significant ambiguity relates to the actual number of independent chips in the TF-QKD network experiment. Can the authors please confirm how many independent client chips were used in total? It is suggested that 20 client chips (10xA chips and 10xB chips) were used in the TF-QKD network experiment, each aligned to a different comb line, however the number of client chips is not stated unambiguously. This would help the reader appreciating the scalability of the photonic integration technology used in this work. In relation to this question, how similar/dissimilar are the building blocks on the different chips (laser central wavelengths, intensity modulator ERs, phase modulators Vpi, etc).

1. The number of independent InP QKD client chips employed in our experiments.

We thank the referee for pointing out the ambiguous statement in our original manuscript.

In the first submitted version: the TF QKD network was implemented with two InP QKD client chips and 10 different wavelength channels determined by the microcomb lines. **Now this set of old data has been removed to Figure S8 and Table S6 in Supplementary Information.**



In the revised version: the TF QKD network is now completely reimplemented using **20 independent TF-QKD transmitter chips** (see a new Fig.1c, where each PCB carries two InP chips to reduce packaging costs). These 20 InP chips are fabricated on a 3-inch wafer using foundry-level manufacture (see their fabrication in revised Supplementary Section 1, and see their characterisations in this letter and the significantly revised Fig.2) and they are now simultaneously deployed. The TF QKD network between 20 client chips is centralised with a microcomb laser, which provides all chip-level resources required for parallel and simultaneous 20-user QKDs in the network. **All phase tracking and QKD data have been re-collected and reported in new Fig.3 and Fig.4.**

Phase tracking and QKD were implemented sequentially between each paired QKD client chips for each specific wavelength channel, with all other WDM channels leaving continuously running to emulate a parallel operation (please see our response to the referee's next comments). We implement sequential measurement on these 20 independent TF-QKD chips through 10 WDM channels because of the limited resources, such as RF electronic controls and synchronisations in our lab. We used commercial electronics (costs about \$70k per paired QKDs), and such electronic controls could be replaced by monolithic electronics and FPGAs in future to further reduce costs, which however is beyond the scope of our current laboratory demonstration.

In the revised **Abstract and Introduction**, we have rephrased the statement and unambiguously represent what we have achieved in this proof-of-principle demonstration of a chip-based TF-QKD network.

Quantum key distribution (QKD) leverages the principles of quantum mechanics to enable provably secure communication^{1,2}. One significant challenge persists in the development of large-scale QKD networks with a large number of clients over long communication-distances^{3,4}. While quantum relays continue to pose practical difficulties⁵, existing trusted node networks^{6–10}, point-to-multipoint networks^{11,12}, and wavelength-multiplexed entanglement networks^{13,14}, encounter issues such as reliance on trusted intermediaries or limited distances. Twin-field (TF)-QKD provides a compelling architecture that can overcome those issues while enhancing communication-distance¹⁵. Though long-distance point-to-point TF-QKD have been achieved^{16–22}, realising large-scale network requires scalable quantum devices. Here, we report proof-of-principle demonstration of integrated-photonic TF-QKD network with exceptional scalability and reliability. This network integrates twenty independent client-side QKD transmitter chips with a server-node-integrated optical microcomb chip. The microcomb generates a broad spectrum of ultra-low-noise coherent frequency combs with Hertz-level linewidths, which serve as seeds and references for all client chips. Each chip regenerates ultra-low-noise light phase-locked to microcombs and prepares quantum keys, achieving high performance, identical operation and high scalability through monolithic photonic integration. We sequentially implement pairwise QKD across twenty client chips through ten wavelength-multiplexed channels, with each surpassing the repeaterless bound at 370 kilometres in spooled fibre, achieving a networking capability (client-pairs $\times$ communication-distance) of 3,700 kilometres. Combining mass-manufacturability, cost-effectiveness and high scalability of integrated photonics with long-distance quantum communication represents a viable path to large-scale quantum networks.

works faces substantial technical challenges. These include development of many ultra-low-noise coherent laser sources, mass manufacture of identical, high-performance QKD chips that maintain uniformity across all client nodes, and system-level integration that enables scalable quantum node operation and quantum channel transmission, while remaining compatible with existing phase tracking. They collectively represent the fundamental requirements for TF-QKD network infrastructure, demanding simultaneous advances in photonic integration, manufacturing scalability, and system control.

Here, we present proof-of-principle laboratory demonstration of user-massively-scalable and long-haul TF-QKD network enabled by integrated photonics, named as "*Weiming Quantum Chip-Network*". Our integrated-photonic QKD network comprises a central server chip that integrates an optical microresonator frequency comb (microcomb) on silicon nitride (Si₃N₄) platform, and 20 copies of independent client-side QKD transmitter chips that monolithically integrate all essential components for key preparation based on indium phosphide (InP) photonic circuits. These InP QKD client chips, fabricated on a 3-inch wafer, were characterised with identically high performance, reproducibility, and high operational yield, thus providing scalable quantum devices for network implementations. We harness integrated microcomb technology, which has revolutionized classical photonics^{24–26}, to dramatically enhance TF-QKD network's scalability and reliability by delivering a large number of ultra-low-noise, phase-coherent comb lasers for WDM-based networks across distributed client chips. We implemented the pairwise TF-QKD between 20 InP client chips through 10 wavelength-multiplexed channels aligned with microcomb lines, realising a total network spanning capability $NL/2 = 3700$ km (where $N=20$, $L=370$) without any trusted relays, after 10 trillion cycles of communication tested.

We also want to take this opportunity to explicitly explain the main distinction between the revised and original manuscripts, which mainly addresses the key concern raised by the referee: **whether a substantial number of InP QKD client chips were simultaneously deployed in this large-scale TF-QKD network?** Addressing this concern is indeed important, because it can answer a question: **whether integrated quantum photonic devices (including the microcomb server chip and QKD client chips), can indeed achieve the claimed scalability, when implemented with TF protocols and WDM architectures.**

To answer this question, we posit two pivotal aspects:

(1) The capability of generalised device architectures to accommodate diverse protocol requirements across multiple users (e.g., reconfigurability for WDM network implementations).

(2) The feasibility of mass-manufacturing integrated QKD transmitter chips with uniform performance through cost-efficient fabrication processes, while maintaining high-fidelity specifications for advanced QKD protocols. In the original version, we focused primarily on the (1) aspect. This was achieved by demonstrating the ultra-high coherent microcomb with a wide spectrum range at server's side and employing 2 QKD chips configured with different wavelength settings sequentially (mimicking multi-user scenarios) to construct such a network.

However, we fully concur with the referee's insights regarding the pivotal challenge in such large-scale network applications: whether InP QKD client chips can provide high scalability through the fabrication and operation of multiple nearly identical chips. This directly corresponds to the (2) aspect. We fully agree with the referee that full characterisation of independent InP QKD chips (including fabrication, operation, and building blocks), is essential for demonstrating the practical scalability central to this work. Such systematic validation not only establishes the reproducibility of integrated quantum photonics, but also highlights several essential advantages: miniaturisation, cost efficiency, and manufacturability — key enablers for future large-scale quantum networks. Following the referee's valuable suggestion, we have undertaken an extensive characterisation, packaging and testing of 20 copies of fabricated InP QKD transmitter chips to rigorously evaluate their yield, reproducibility, and scalability. This comprehensive study further validates the system-level operation of our TF-QKD network, which integrates 20 client chips with a centralised microcomb chip.

2. Full characterisations of 20 copies of InP QKD chips (fabrication, operation, and building blocks)

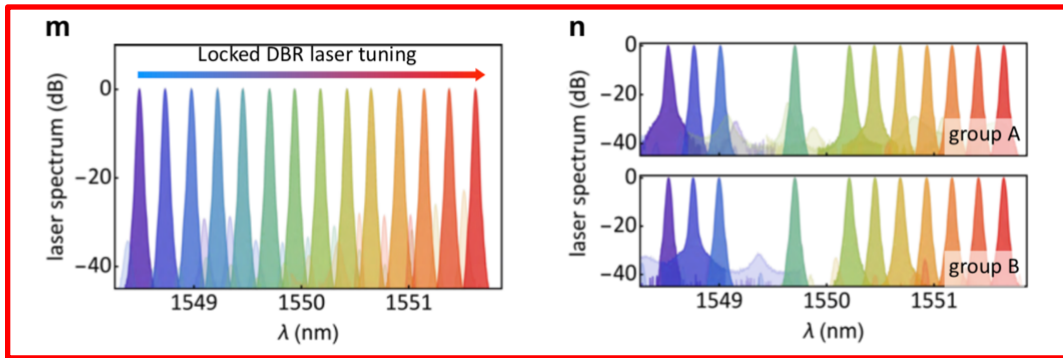
The 20 InP client chips used in our work were fabricated on a single 3-inch wafer. These chips were fabricated in the Smart Photonics Foundry in collaboration with colleagues in Eindhoven University of Technology. **As the referee suggested, in the revised manuscript, a brief introduction to the fabrication process of these InP client chips has been added in the Supplementary Section 1.**

Integrated InP QKD client-chips: The quantum key distribution (QKD) transmitter client-chips were monolithically fabricated on a 3-inch indium phosphide (InP) photonic integration platform, including all functional components for QKD such as distributed Bragg reflector (DBR) lasers, intensity modulators (IMs), phase modulators (PMs), attenuators, and photodiodes (for calibration). The *n*-doped substrate serves as a common ground contact across the entire wafer. Device fabrication began with metalorganic vapour phase epitaxy (MOVPE) to grow different active and passive regions or structures, followed by a series of precision etching processes to define the various photonic waveguide components. The active regions incorporated multiple InGaAsP quantum well layers sandwiched between quaternary InGaAsP barrier layers, with semiconductor optical amplifiers (SOAs) formed by selectively etching the active layers to create gain sections. Passive waveguide regions were realised using low-doped InGaAsP layers with a 1.25 μm bandwidth, optimised for minimal absorption in the telecommunications C-band. The upper cladding consisted of sequentially deposited p-doped InP and InGaAs layers. Electrical isolation between components was achieved through controlled etching of the top cladding layers, which separated the active regions and reverse-biased passive sections. Following passivation and planarisation using polyimide organic polymer, the final processing steps involved depositing top metal contacts and patterning coplanar waveguide transmission lines to establish electrical interconnects and signal routing across the chip.

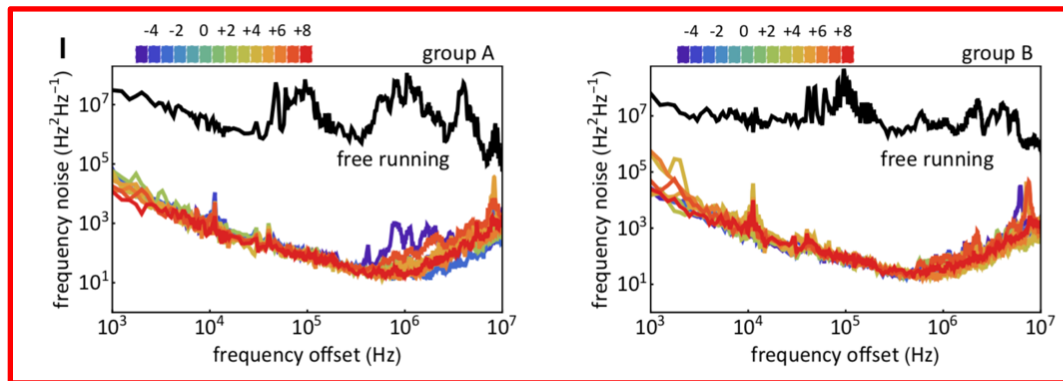
2.1 Full characterisations of 20 independent QKD lasers + references lasers on 20 separated InP chips:

For the InP lasers, we demonstrated two key functionalities: (i) wavelength tunability of lasers across the entire spectral range of the network, and (ii) injection-locked spectra and frequency noise, across 20 separated InP chips, with all performance satisfying the protocol requirements. We didn't show the characterisation of lasers' initial spectra as the lasing exhibits multi-parametric dependencies, including configurations of distributed Bragg reflector (DBR) and voltage/current in semiconductor optical amplifier (SOA), and thermal tuning. This inherent variability precludes the establishment of universal initial characterisation metrics across all devices. We show the significant reduction of frequency noises before and after the injection-locking operation across 20 separated InP chips. We also employed the wavelength tuning capability and spectral/linewidth characteristics after injection-locking operation, which directly reflect their functional reliability in actual operating conditions.

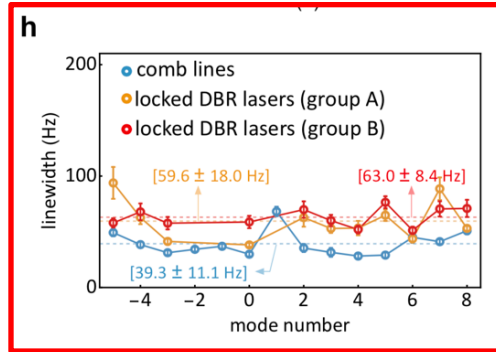
In a new Fig.2m, we have now added the measured optical spectra of a single laser continually tuning to the microcomb lines, and in a new Fig.2n, we have now added the measured optical spectra of 20 independent QKD lasers (10 lasers in group A and 10 lasers in group B in the network) on 20 separated InP chips and additional reference lasers (10 lasers in total, we show 2 lasers as examples in Fig.2n), where those independent lasers on separated chips have been locked to the central microcomb's lines to regenerate the quantum signals and reference signal.



In a new Fig.2l, we have now reported the measured laser frequency noises when they are free running and injection-locked, for those 20 independent QKD lasers (10 lasers in group A + 10 lasers in group B) on 20 separated InP chips and 2 additional reference lasers.



In a new Fig.2h, we have reported the measured laser linewidth when they are injection-locked, for those 20 independent QKD lasers (10 lasers in group A + 10 lasers in group B) on 20 separated InP chips and 2 additional reference lasers. Those data for microcomb are now also combined in the new Fig.2g.



Details of laser characterisations have been added in the revised main text.

for pulsation and key encoding, as illustrated in Fig.2a. We characterise the regeneration of ultra-low-noise light in those wavelength-tunable slave lasers across 20 InP chips. After locking the DBR lasers to the comb lines, we re-characterised frequency noises, as shown in Fig.2l. Figure 2h summarises measured linewidths for comb lines and locked local lasers, demonstrating substantial frequency noise suppression that achieves intrinsic linewidths of around 60 Hz for TF-QKD. As shown in Fig.2m, a client-chip locked DBR laser achieve 3.2 nm continuous wavelength tuning, spanning the λ_{-5} to λ_{+8} range. All DBR lasers across the 20 chips demonstrate independent wavelength tunability and injection locking to comb lines, with each achieving > 30 dB side-mode suppression (Fig.2n). These results demonstrate the capability of massive integration and operation of low-noise lasers for scalable WDM-based TF-QKD networks.

Details of laser characterisations have been added in the Fig.2 caption.

zero V_{π} or visibility indicate 3 hardware failure of modulators, resulting in a 97.5% yield. (l), Frequency noise characterisation of phase-locked slave lasers on the QKD client-chips, showing comparable performance to the microcomb (see summary in (h)). In (g) and (i), free-running lasers (black) are plot for comparison. (m), Continuous tuning spectrum of a single client-laser, aligning and phase-locking to specific comb lines. (n), Spectra of injection-locked slave lasers on different client-chips. Error bars denote the ± 1 standard deviation of measured data.

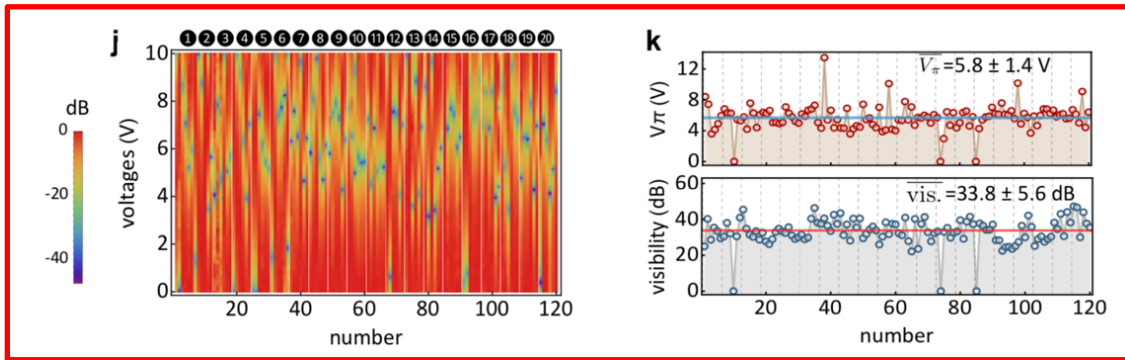
In the Supplementary Information Section 4, we have added details of microcomb generation.

Dark-pulse microcomb generation at the server chip: The Si_3N_4 microresonator and integrated distributed feedback (DFB) laser were mounted on the thermoelectric coolers, respectively with 1 mK temperature control accuracy. The DFB laser chip was controlled by a six-axis stage to precisely adjust the coupling angle and air gap between chips. Under the condition of small detuning between the laser and

microresonator's mode, we implemented 1 kHz sawtooth-wave current scanning of the DFB laser while performing synchronous coupling air gap adjustments to identify the optimal dark-pulse frequency comb generation regime. This procedure enabled the determination of the optimised laser current and coupling air gap parameters, allowing subsequent turnkey acquisition of the microcomb outputs through direct loading of predetermined current values to the DFB laser under invariant experimental conditions. An optical isolator was inserted at the output of the microcomb to prevent reflected noise light from disturbing the locking condition. Then, part of the microcomb was fed into the photodiode, optical spectrum analyser and phase noise analyser for monitoring and performance characterisation. The desired comb lines ranging from λ_{-5} to λ_{-3} and λ_{+2} to λ_{+8} were selected and intensity equalized with a waveshaper. An Erbium-doped fibre amplifier was used to ensure that the comb had an intensity of at least -20 dBm on-chip power when injected as seed lights onto the QKD transmitter chips. The spacing between different wavelength channels was 30.03 GHz (equal to the FSR of the microresonator), misaligning with the standard ITU channel spacing. Integrated microcombs matching standard ITU channel spacing (e.g., 50/100 GHz) can be readily implemented⁷⁴, enabling full utilisation of mature WDM components for wavelength allocation and spectral filtering. This could facilitate cost-effective deployment in real-field quantum communication networks. After the comb line assignment based on network configuration, polarisation controllers were used to align the polarisation of the seed lights with the optical mode on client chips.

2.2 Full characterisations of 120 independent modulators on 20 separated InP chips:

As the referee highlighted and suggested, for QKD protocols based on weak coherent states, the key parameters of modulators are the V_π of phase modulators and modulation visibility (i.e., extinction ratio, ER) of intensity modulators, because these parameters fundamentally determine the driving efficiency and bit error rate (BER) of the QKD system. We have now implemented full characterisations of 120 independent PMs and IMs on 20 separated InP chips, and results are reported in new Fig.2j, Fig.2k and Fig.2i. We therefore demonstrate high yield modulators with a V_π of 5.8 ± 1.4 V and a high modulation visibility of 33.8 ± 5.6 dB. All EO modulators functioned as designed under normal operation, while 3 out of 120 modulators showed failures due to fabrication imperfections, yielding a high yield rate of 97.5%. Fortunately, we could implement a single-drive configuration using one of the EOPMs in each IM, instead of a push-pull dual-drive configuration using two EOPMs in each IM, ensuring fully operational QKD networks using 20 independent InP chips.



In the revised main text Page 4, we have added a paragraph to describe the details of InP chip characterisations.

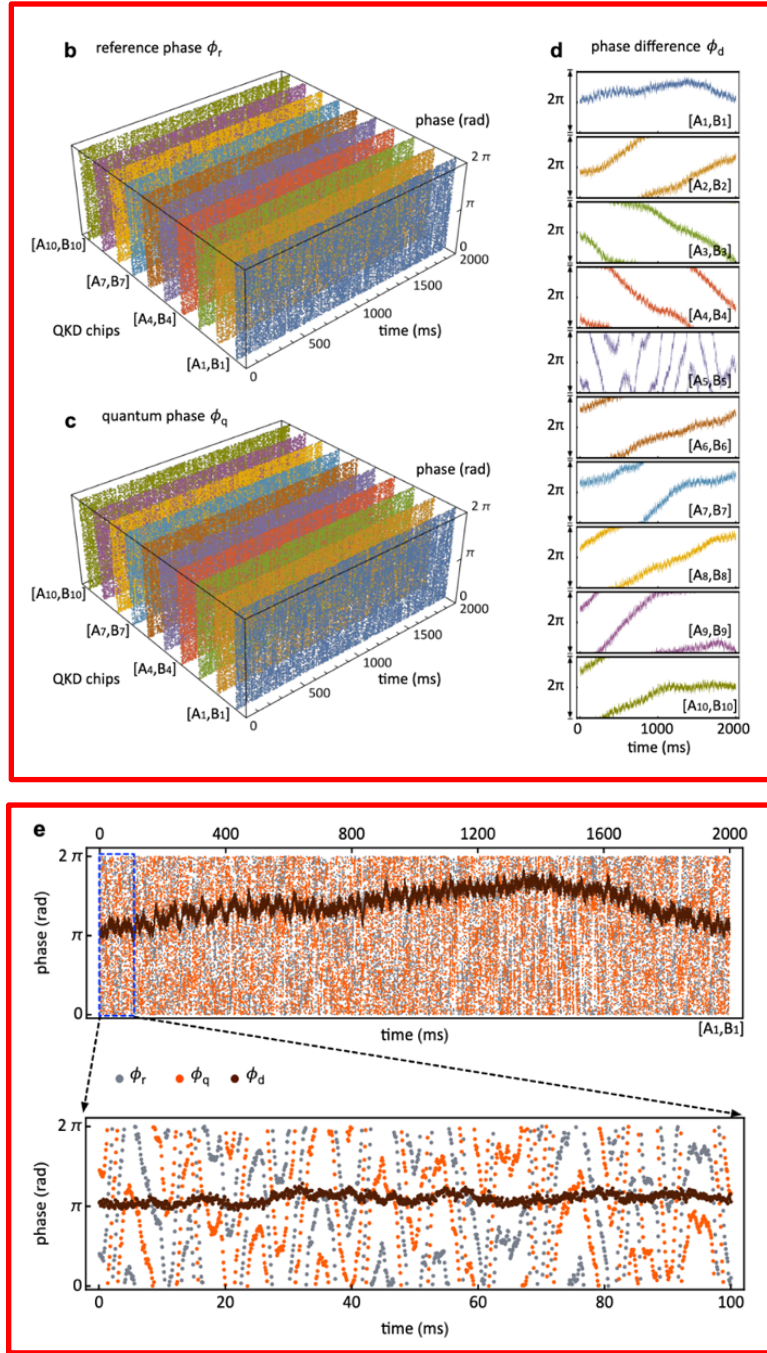
The phase modulation was achieved using a single-arm electro-optic PM (EOPM), while intensity modulation was implemented using Mach-Zehnder modulators (MZMs) with dual PM arms (1.25 mm length, 25 GHz bandwidth) for loss balance and high extinction ratio. Figure 2j reports measured modulation curves for all EOPMs in IMs. It reveals 117 of 120 EOPMs (97.5% yield) functioning as designed across all 20 chips, with three hardware failures. These modulators exhibited consistent performance, as shown in Fig. 2k, with an average V_π of 5.8 ± 1.4 V and interference visibility of 33.8 ± 5.6 dB.

In the Supplementary Information Section 4, we have added details of quantum keys encoding at the InP client chips.

Quantum keys encoding at the InP client chips: Laser diode controllers were used to control the SOA section of on-chip DBR lasers and the chip's temperature, and the DBRs were controlled with additional voltage sources. The frequency detuning with the microcomb seed light could be carefully controlled to achieve injection locking conditions. The detuning range was initially determined by synchronously adjusting above operating parameters to make robust injection-locking operation. Subsequently, with all parameters (including seed light power) maintained constant, stable locking states can be reliably achieved during each experimental run through rapid SOA current scanning until reaching predetermined values. Such procedures allow for individual calibration of the lasers across all 20 client chips. The DBR lasers were running in continuous mode. For pulsation, electrical signals from high-speed arbitrary waveform generators (AWGs) were amplified and mixed with DC bias signals, and then fed into the IMs III. Additional AWGs were used to generate the electrical control signals for the PM I and IM I, II according to the sequence shown in Fig. 3a to finish the phase randomisation and coding, and decoy state preparation and attenuation. Experimental characterisations of optical injection locking of local DBR lasers and modulators are provided in Fig. 2 of the main text. Figures 2j and 2k demonstrate the high yield of our electro-optic modulators, with 97.5% (117 of 120) functioning as designed under normal operating conditions, while 3 devices exhibited failures due to fabrication imperfections. The device's design allows for flexible configuration. We successfully implemented a single-drive scheme using one electro-optic PM (EOPM) per IM as an alternative to the dual-drive push-pull configuration (which would require two EOPMs per IM). This adaptability ensured full operational capability across all 20 independent InP chips in the QKD network.

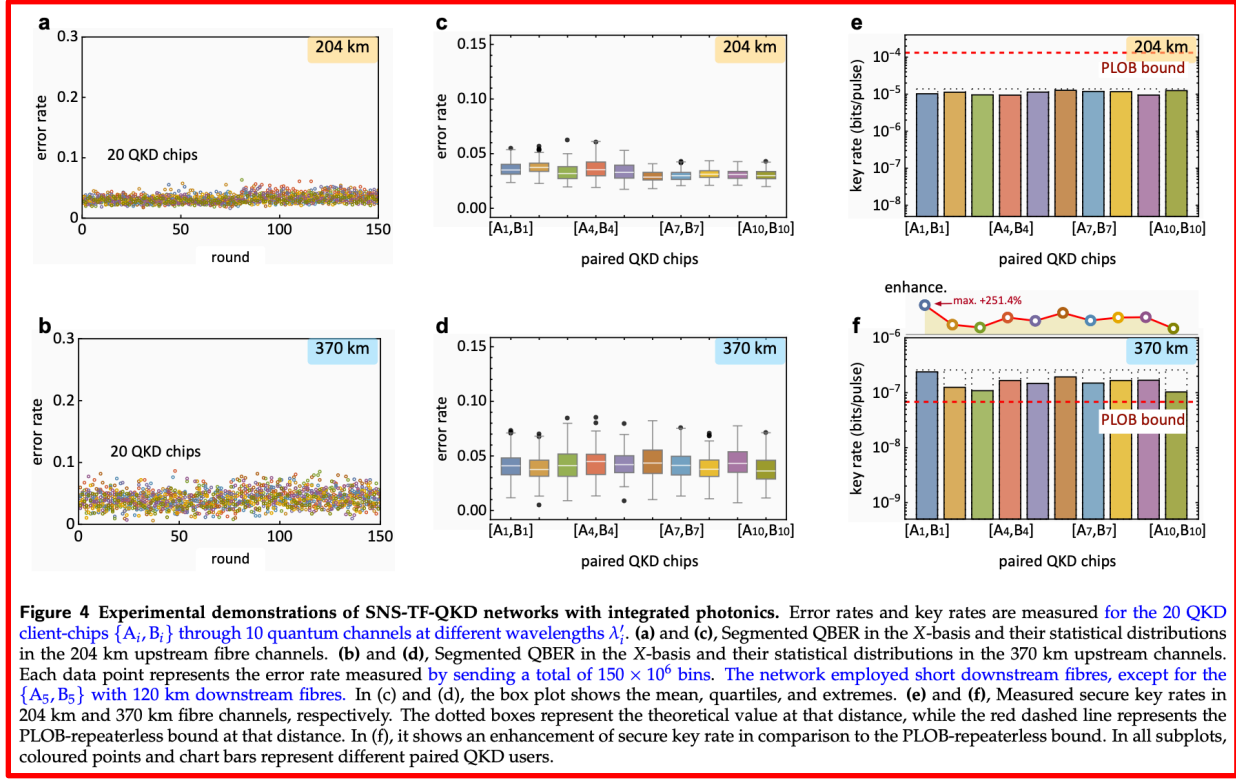
3. Demonstration of TF-QKD network with 20 InP client-chips and a microcomb chip

We have reimplemented the entire TF-QKD network using **20 TF-QKD chips**. Phase tracking between those 10 pairwise client-chips $\{A_i, B_i\}$ is reported in the updated Fig.3.

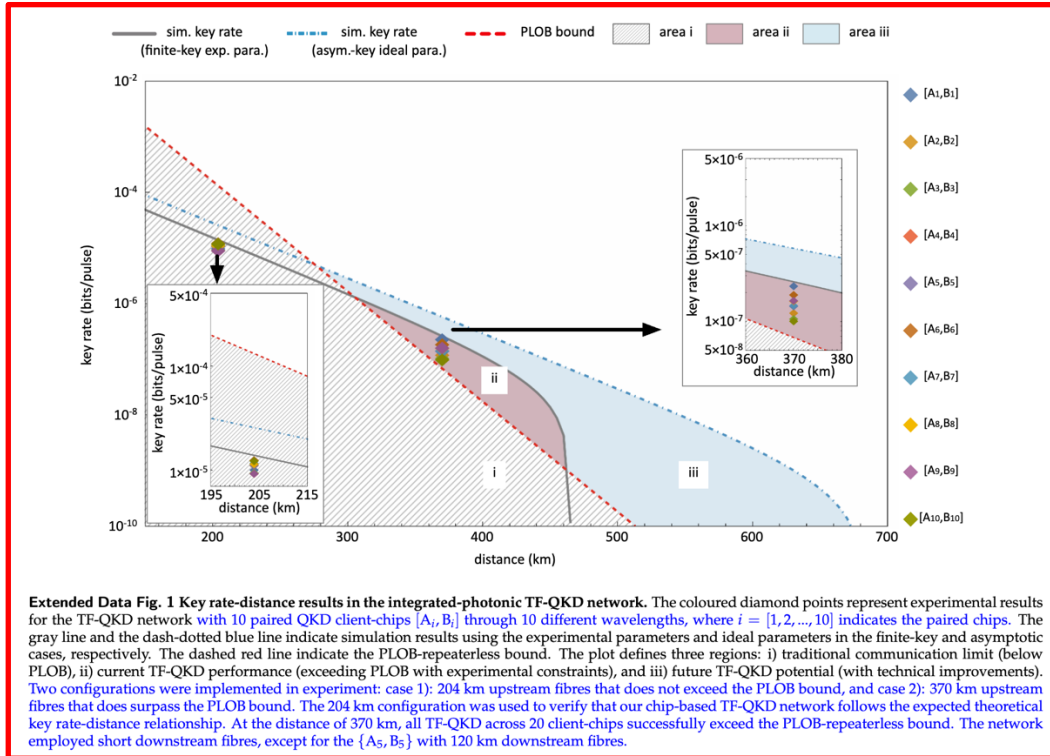


NEW PHASE TRACKING RESULTS: Fig.3...(b) and (c), Experimental characterisation of phases across the fibre links between those 10 pairwise client-chips $\{A_i, B_i\}$ and the server chip: (b), phases for the reference signals (Φ_r) at the wavelength of λ_0 , (c), phases for the quantum signals (Φ_q) at the wavelength of λ'_i , and (d), their relative phase differences $\Phi_d = \Phi_r - \Phi_q$[e], An example of phase distributions for the $\{A1, B1\}$ paired QKD chips. Inset: zoom-in view of the initial 100 ms window.

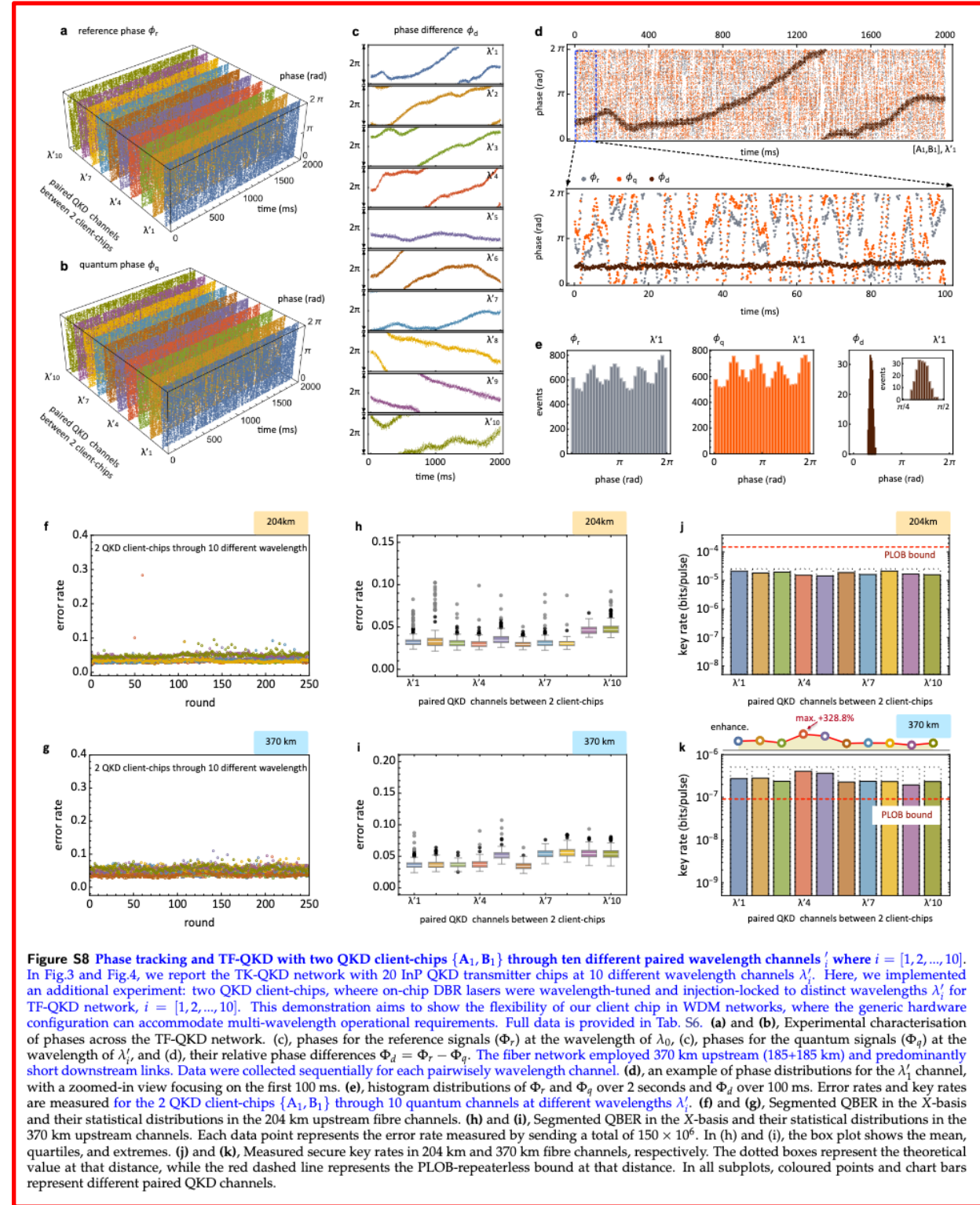
NEW QKD RESULTS: Error rates and key rates for the 10 pairwise client-chips $\{A_i, B_i\}$, in total 20 chips, are reported in the new Fig.4.



Extended Data Fig.1, along with additional supporting data is provided in the Supplementary Information.



OLD PHASE TRACKING and QKD RESULTS: The experimental data of the previous TF QKD network with 2 InP transmitter chips operating at different wavelengths has been moved to [Supplementary Information Fig.S8](#).



Full experimental data for 20 QKD client chips linked via 10 different wavelengths (new data), and 2 QKD client chips linked via 10 different wavelengths (old data), have been provided in Tables S5 and S6, respectively.

In the revised **Abstract, Introduction, and the caption of new Fig.2, Fig.3 and Fig.4**, we have now clarified the implementation of 20 QKD client-chips in the current TF-QKD network.

In the revised main text, Page 2, we have added a sentence: *"20 copies of InP QKD chips synergistically leveraged in this work are shown in Fig. 1c."*

In the revised main text, Page 4, we have rephrased a sentence as: *"Twenty InP chips (footprint $4.6 \times 2 \text{ mm}^2$ each, see Fig.2i) are divided to group A and group B, to implement pairwise TF-QKD between the two chips $\{A_i, B_i\}$, where $i = [1, 2, \dots, 10]$ represents paired-users sharing identical wavelengths λ'_i . λ'_i are aligned with microcomb lines, remapping from $\lambda-5$ to $\lambda-3$ and $\lambda+2$ to $\lambda+8$."*

In the revised main text, Page 6, we have rephrased a sentence as: *"We implemented lab-scale proof-of-principle quantum network of 20 QKD client-chips linked via 10 WDM channels. Phase tracking and key distribution were sequentially executed between paired chips $\{A_i, B_i\}$ due to resource constraints in electronic controls and clock synchronisation. All 10 WDM channels maintained parallel fibre transmission interconnecting 20 QKD chips during sequential QKD operation, with non-target channels at high power to estimate an upper bound for crosstalk and noise (emulating realistic scenarios)."*

In the revised main text, Page 6, we have rephrased a sentence as: *"The QKD network contains $N = 20$ client chips (that is, 10 paired chips connected via 10 WDM channels), achieving a total networking capability of $NL/2 = 3700 \text{ km}$."*

In the revised main text, Page 7, we have rephrased a sentence as: *"Secure quantum keys were then distributed across the network between 20 QKD client-chips...."*

We have rephrased the Extended Data Fig.2 (Fig.5 in the initial submitted version).

Extended Data Fig. 2 Summary of state-of-the-art QKD and QKD networks without trusted intermediate nodes. The size of points in the visualisation represents the total quantum networking capability of $NL/2$, where N denotes the number of QKD users and L signifies the channel distance. In the TF-QKD network presented in this work, we achieved a total quantum networking capability of $NL/2 = 3700 \text{ km}$, with $N = 20$ chip-based QKD users and $L = 370 \text{ km}$ channel distance. Some notable demonstrations of QKD and QKD networks include: the longest satellite-based QKD in ref.[63]; the longest fibre-based TF-QKD in ref.[20]; deployed TF-QKD in ref.[22]; the longest MDI-QKD in ref.[64]; longest chip-based MDI QKD in ref.[41]; a three-user MDI-QKD network in ref.[65]. Results from QKD networks relying on trusted intermediate nodes are excluded from this summary.

Throughout the Supplementary Information, we have now clarified the implementation of 20 QKD client-chips in the current TF-QKD network.

We appreciate the referee's insightful comment regarding the role of microcomb lasers and TF QKD chips in the TF-QKD network. We have now emphasised a critical advancement: the scalability of InP-based QKD chips, which we have now demonstrated in the revised manuscript. To ensure experimental results are presented with roughly equal rigour, and following the Editor's suggestion to streamline the title, we have revised it to: **"Large-scale Quantum Communication Networks with Integrated Photonics"** (replacing the initial submitted version: "Scaling Quantum Communication Networks with Microcomb-Driven Integrated Photonics").

In summary, these full characterisations of 20 copies of InP QKD chips have verified the high yield and reproducibility of all lasers and modulators on these InP chips, demonstrating their strong scalability for large-scale implementation of QKD networks with integrated QKD transmitters and microcomb lasers. Given these verified highly identical InP transmitter chips, we have now recollected every data point in Fig.3 and Fig.4 to demonstrate the microcomb-driven 20 InP client chips-based TF QKD system. We once again express our gratitude to the referee for the profound and visionary insights. We are confident that the current version has been substantially improved, with the results representing an important step toward the application of integrated photonic technologies to quantum communication networks.

On several occasions it is stated that the network spans 3700 km of fibre:

Abstract: "Our network parallels TF-QKDs between transmitter chips across twenty channels, with each paired QKD exceeding the repeaterless bound over a 370-kilometre spooled fibre, resulting in a total distance of 3700 kilometres."

Page 1, col. 2: "Our quantum network covers a total communication distance $NL/2$ exceeding 3700 km without any trusted relays, after 10 trillion cycles of communication tested."

Page 5: "The QKD client chips were symmetrically linked to the server via long fibres spanning up to 185 km, resulting in a maximum distance of $L = 370$ km between each user pair. The network comprises $N = 20$ channels, yielding a total communication distance of $NL = 3700$ km."

Caption of Fig. 5: "In the TF-QKD network presented in this work, we achieved a total communication distance of $NL/2 = 3700$ km, with $N = 20$ users and $L = 370$ km channel distance."

Page 7, col. 1: "Through the validation of bit transmission, the architecture and hardware have been proven capable of supporting many-channel networks accommodating 20 clients, spanning a total communication distance exceeding 3700 km, with each channel enabling the distribution of secure keys that surpass the repeaterless bound."

Table S5 mentions "20 different paired TF-QKD users in the network".

However, it seems that this is in fact a cumulated distance. It appears that there are only 2 fibre spools of 185km, one used to multiplex the A client chips, and another one use to multiplex the B client chips. To avoid leading the general reader into assuming that 3700km of spooled fibres were used in the experiment, the 3700km should be mentioned as a capability rather than a total distance. Terms like "spanning a total communication distance of 3700km" are very misleading to the general readership.

Likewise, there are not $N = 20$ independent channels. There are 10 wavelengths traveling into the same fibre. This makes at most 10 effective channels. In this statement the authors seem to have made a confusion between the number of clients (defined as N) and the number of channels. The intention of the authors to consider each wavelength as a distinct channel is understandable, however the problem is again that the statement may be misleading. The experimental conditions are not clearly stated in the abstract, introduction or conclusion. The figures, abstract and comments refer to the perspective and concept of a deployed TF-QKD network rather than an actual TF-QKD network proof-of-concept experiment, and this is misleading to the reader. Table S5 also mentions 20 different paired clients instead of 20 different settings.

We sincerely appreciate the referee for meticulously pointing out these inaccurate descriptions in the original manuscript. We have now carefully checked out all the statements throughout the revised manuscript to ensure a precise presentation of our work.

As the referee suggested, throughout the revised manuscript, we have now replaced the descriptions of "total communication distance 3700 km" with "**3700 km networking capacity (paired clients $\times$ communication distance)**".

We have now rephrased "channels" to "wavelength channels" or "wavelength multiplexed channels" or "WDM channels". We have now clarified the relationship between the number of client chips (N), wavelength channels ($N/2$), and fibre channels. **We clarified that this work was accomplished in the lab with 20 independent QKD transmitter chips through 10 WDM channels and all QKD data were obtained sequentially for each paired chips at a wavelength channel.** The following are some main modifications in the revised main text. Supplementary Information has also been revised accordingly.

In the revised Abstract, we have rephrased: “Here, we report proof-of-principle demonstration of integrated-photonics TF-QKD network with exceptional scalability and reliability.”

In the revised Abstract, we have rephrased: “We sequentially implement pairwise QKD across twenty client chips through ten wavelength-multiplexed channels, with each surpassing the repeaterless bound at 370 kilometres in spooled fibre, achieving a networking capability (client-pairs $\times$ communication-distance) of 3,700 kilometres.”

In the revised Introduction, we have rephrased: “Here, we present proof-of-principle laboratory demonstration of user-massively-scalable and long-haul TF-QKD network enabled by integrated photonics, named as “Weiming Quantum Chip-Network”.”

In the revised Introduction, we have added a sentence: “We implemented the pairwise TF-QKD between 20 InP client chips through 10 wavelength-multiplexed channels aligned with microcomb lines, realising a total network spanning capability $NL/2 = 3700$ km (where $N=20$, $L=370$) without any trusted relays, after 10 trillion cycles of communication tested.”

In the revised main text, Page 6, we have rephrased a sentence as: “The QKD network contains $N = 20$ client chips (that is, 10 paired chips connected via 10 WDM channels), achieving a total networking capability of $NL/2 = 3700$ km.”

In the Fig.2 caption, we have now rephrased: “Paired client-chips of $\{A_i, B_i\}$ send quantum states through the λ_i -channel in long-haul upstream fibres (where all wavelength channels are multiplexed), with single-photon interference measurements at the server node returning secure keys.”

In the Fig.4 caption, we have now rephrased: “Error rates and key rates are measured for the 20 QKD client-chips $\{A_i, B_i\}$ through 10 quantum channels at different wavelengths λ_i .”

In the revised main text, Page 4, we have rephrased a sentence as: “Twenty InP chips (footprint 4.6×2 mm² each, see Fig.2i) are divided to group A and group B, to implement pairwise TF-QKD between the two chips $\{A_i, B_i\}$, where $i = [1, 2, \dots, 10]$ represents paired-users sharing identical wavelengths λ_i . λ_i are aligned with microcomb lines, remapping from $\lambda-5$ to $\lambda-3$ and $\lambda+2$ to $\lambda+8$.”

In the revised main text, Page 6, we have rephrased a sentence as: “We implemented lab-scale proof-of-principle quantum network of 20 QKD client-chips linked via 10 WDM channels.”

In the revised Conclusion, we have rephrased a sentence: “In summary, we have implemented a proof-of-principle integrated-photonics QKD network, demonstrating high scalability and reliability. Through the validation of bit transmission, the architecture and hardware have been proven capable of supporting many-user networks accommodating 20 client-chips, spanning a total networking capability exceeding 3700 km, with each channel enabling the distribution of secure keys that surpass the repeaterless bound.”

In the revised Conclusion, we have added a sentence: “While this is currently a lab-scale demonstration, our integrated quantum photonic devices and technologies can be readily extended to field-deployable QKD networks (see discussions in Supplementary Information 5).”

We have also added a new section, Supplementary Section 5 “Towards real-field implementation of integrated-photonics TF-QKD networks”, to discuss how to extend current proof-of-principle networks toward deployed networks.

Throughout the Supplementary Information, we have now clarified that the current TF-QKD implementation is a lab-scale proof-of-principle demonstration, and the demonstrated 3700km represents its networking capability (paired clients $\times$ communication distance).

It is not clear whether the phase tracking done in parallel for all channels, or sequentially, pair by pair. If the channels are multiplexed in the same fibre, how was the phase stabilization done in parallel? How many independent phase modulators and SNSPD channels are used to stabilize the reference central comb line, λ_0 ?

We thank the referee for pointing out the unclear descriptions of phase tracking in the original manuscript. In the revised manuscript, we have reimplemented the phase tracking (new Fig.3) and TF-QKD network (new Fig.4) with 20 TF-QKD chips. In our experiment, phase tracking was implemented sequentially, pair by pair, so as the QKD between 20 InP chips. Again, the reason for implementing sequential phase tracking and 20 chip QKD through 10 WDM channels is because of the limited resources in our lab. In the revised manuscript, we have clarified the sequential phase tracking in the 20 client-chip TF-QKD network (please see our response to the referee's previous two comments).

In particular, we have added a paragraph in the main text Page 6.

We implemented lab-scale proof-of-principle quantum network of 20 QKD client-chips linked via 10 WDM channels. Phase tracking and key distribution were sequentially executed between paired chips $\{A_i, B_i\}$ due to resource constraints in electronic controls and clock synchronisation. All 10 WDM channels maintained parallel fibre transmission interconnecting 20 QKD chips during sequential QKD operation, with non-target channels at high power to estimate an upper bound for crosstalk and noise (emulating realistic scenarios). Our implementation combines established dual- λ phase tracking and postselection^{20,48,49} maintaining system simplicity while ensuring sufficient stability for this demonstration, with microcomb-enabled coherent WDM, which together provide an efficient solution for TF-QKD network. Details are provided in Supplementary Information 4.

This method effectively emulates the simultaneous (global) phase tracking across all wavelength channels which are designed to copropagating between two metropolitan areas in the network. We maintained parallel transmission of all other quantum signals in the same fibre. This configuration has set the worst case of crosstalk and noise photons that may increase QBER, which we have rigorously analysed and experimentally validated. We have added detailed analysis and experimental results in a revised Supplementary Section 4.1: "WDMed Quantum channels in fibres":

WDMed Quantum channels in fibres: The reference and quantum signals were wavelength-multiplexed and transmitted in the long-haul upstream fibre spool back to the server node simultaneously. The upstream channel distance from Alices' and Bobs' node to the central server node and corresponding fibre losses are provided in Table S3. Constrained by limited RF resources, we simulated concurrent multi-user communication by implementing the whole quantum state encoding procedure in sequence for the selected user pair while leaving other non-target wavelength signals unmodulated and directly injecting into the upstream fibre channels. To evaluate worst-case crosstalk, these non-target wavelength signals were maintained at maximum intensity levels required for phase tracking (see Section 4.3). To simplify the system for a proof-of-principle demonstration of TF-QKD network, the downstream fibres from the microcomb to the QKD client-chips were replaced by short fibres in most cases, except for the user pair $\{A_5, B_5\}$, where 120 km-length (60+60 km) downstream fibres were used. We confirm comparable phase drift and phase tracking for short and long downstream fibres in Fig.3 and implement TF-QKD in both cases in Fig.4. Detailed performance characterisation regarding the introduction of long downstream fibres is presented in the main text and further discussed in Section 5.1.

We would like to emphasise that our streamlined approach that combines dual- λ methods and microcomb-enabled coherent WDM can simplify phase tracking, providing an efficient solution for multi-wavelength, multi-user, long-haul TF-QKD networks. In our network configuration in Fig.1a, users within the same metropolitan zone share common upstream/downstream backbone fibres (spanning hundreds of kilometres) connecting

the server and intermediate nodes, while requiring dedicated short-reach fibres between client nodes and the intermediate node, resulting in each client-server connection comprising both shared long-haul and short fibre segments. When these dedicated fibres are sufficiently short with slow phase drift rates, metropolitan users can share a common reference wavelength (because of the locked phases between all comb bins generated by the same high-stability microcomb) for phase tracking instead of requiring individual reference wavelengths. Phase postselection implementation announces all reference wavelength phase shifts, enabling neighbouring users to select appropriate phase windows for data sifting. When the dedicated fibres' length becomes excessive, the phase drifts accelerate, necessitating separate reference and quantum wavelengths for each user. For our experimental demonstration under stable laboratory conditions, we employed a common reference wavelength λ_0 with sequential phase tracking for user pairs while maintaining all other quantum signal transmissions (without detection). Statistical characteristics of phase shifts in the fibre spools demonstrated temporal stationarity (see new results in Fig.3), thereby validating this method for evaluating simultaneous phase tracking across all communication channels. We have now added these analyses and discussion in the new Supplementary Section 4.3.

The objective of this study is to establish a proof-of-concept for integrated-photonic TF-QKD networks — with a focus on device-level networking scalability, rather than existing channel-level techniques. Both phase compensation [e.g, Nature Photonics 15, 530–535 (2021), Nature Photonics 16, 154–161 (2022), & Nature Communications 14, 928 (2023)] and postselection [e.g, Phys. Rev. Lett. 123, 100505 (2019), Nature Photonics 15, 570–575 (2021), & Phys. Rev. Lett. 130, 210801 (2023) — the record of 1000 km TF-QKD] have been widely implemented in pioneering TF-QKD experiments. **Our implementation here uses dual- λ phase tracking and postselection**, sufficient for this demonstration while maintaining the system's simplicity.

Importantly, in the context of key rate, there is no fundamental difference between using postselection or phase compensation. This is because with phase randomisation (that is required for decoy states), valid X11-basis events inherently necessitate postselection (Eq. S16).

$$1 - |\cos[(\delta_A - \delta_B) - (\phi_B - \phi_A)]| \leq |\epsilon_\phi|$$

Eq. S16

These global phases act on the user-encoded optical fields and ultimately determine the long-distance single-photon interference visibility. The ultimate phase interval selection depends on the combined effects of $\{\delta_A, \delta_B, \phi_A, \phi_B\}$. Because the values of randomly chosen $\{\delta_A, \delta_B\}$ in phase randomisation are announced publicly for verification, the difference between (i), real-time compensation of the global phases or (ii), real-time tracking with postselection is whether $\phi_B - \phi_A$ could be regarded as a constant preset value $\Delta(t) = \Delta(0)$ or time-varied known value $\Delta(t)$. Both approaches ensure uniform phase distribution of the total relative phases in $[0, 2\pi)$, because the global phases Δ follow the uniform temporal distribution. Thus, **both phase compensation and postselection** methods make identical proportions of effective events satisfying Eq. S16, with no additional event loss and **no difference in key rate**. However, we fully agree with the referee that for field-deployed QKD systems, phase compensation offers a practical advantage by eliminating the additional data sifting required in postselection approaches. In such implementations, phase compensation methods can be independently applied in fibre channels. We have added detailed discussions in Supplementary Section 4.3.

We have significantly revised Supplementary Section 4.3 to explain the dual-lambda and postselection method:

4.3 Global phase tracking with dual- λ method

The raw key obtained from the interference at the server node hinges on ensuring that it receives the signals as anticipated by users, notwithstanding the various signal degradations over long fibres. The primary factor influencing the interference result is the fluctuation of the relative global phases between Alice and Bob, which can be ascribed to phase noise from lasers and accumulated phase shifts in the fibres:

$$\Delta = \phi_A - \phi_B = \Delta_{\text{laser}} + \Delta_{\text{channel}}. \quad (\text{S23})$$

In this work, the upstream and downstream channels form a large-scale closed MZI for the signal transmission. The adoption of ultra-low-noise lasers by injection locking local DBR lasers to microcomb lines, the laser phase noise Δ_{laser} can be significantly reduced. We adopted the dual- λ method to track and estimate phase shifts in channels Δ_{channel} by comparing co-propagating wavelengths, retrieving only residual slow fluctuations undergoing the same fibre. The dual- λ method also helps diminish the noise stemming from double-Rayleigh scattering in the time-multiplexing scheme and enhances the signal duty cycle^{18,75}.

The system tracks global phases between users but without performing active compensation. These global phases act on the user-encoded optical fields and ultimately determine the long-distance single-photon interference visibility (see Eq. S16). The ultimate phase interval selection in the X-basis depends on the combined effects of $\{\delta_A, \delta_B, \phi_A, \phi_B\}$. Because the values of randomly chosen $\{\delta_A, \delta_B\}$ are announced publicly for verification, the difference between (i), real-time compensation of the global phases or (ii), real-time tracking with postselection (which is the case in this work) is whether $\phi_B - \phi_A$ could be regarded as a constant preset value $\Delta(t) = \Delta(0)$ or time-varied known value $\Delta(t)$. Both approaches ensure uniform phase distribution in $[0, 2\pi)$ of the total relative phases, because the global phases Δ follow the uniform temporal distribution. Therefore, both phase compensation and postselection methods yield identical proportions of effective events satisfying Eq. S16, with no additional event loss. Both global phase compensation^{18,19,21} and postselection^{20,48,49} have been widely implemented in TF-QKD experiments. Phase postselection can simplify the system by eliminating feedback loops. In this work, we intentionally adopted phase postselection to streamline system complexity, focusing on demonstrating scalable integrated photonic hardware for TF-QKD networks. That being said, regarding key rate performance, there is no fundamental difference between using post-selection or phase compensation since phase randomisation (required for decoy-state protocols) inherently involves post-selection in X_{11} -basis. However, for field-deployed QKD systems, phase compensation offers a practical advantage by eliminating the additional data sifting step required in post-selection approaches. In such implementations, phase compensation methods can be independently applied in fibre channels.

In our network configuration in Fig.1a, users within the same metropolitan zone share common upstream/downstream backbone fibres (spanning hundreds of kilometres) connecting the server and intermediate nodes, while requiring dedicated short-reach fibres between client nodes and the intermediate node, resulting in each client-server connection comprising both shared long-haul and short fibre segments. When these dedicated fibres are sufficiently short with slow phase drift rates, metropolitan users can share a common reference wavelength (because of the locked phases between all comb lines generated by the same high-stability microcomb) for phase tracking instead of requiring individual reference wavelengths. Our phase postselection implementation announces all reference wavelength phase shifts, enabling neighbouring users to select appropriate phase windows for data sifting. When the dedicated fibres' length becomes excessive, the phase drifts accelerate, necessitating separate reference and quantum wavelengths for each user. For our experimental demonstration under stable laboratory conditions, we employed a common reference wavelength λ_0 with sequential phase tracking for user pairs while maintaining all other quantum signal transmissions (without detection). The statistical characteristics of phase shifts in the fibre spools demonstrated temporal stationarity (see results in Fig.3), validating this method for evaluating simultaneous phase tracking across all channels.

We clarify and summarise several characteristics of the entire phase-locking system, from the server chip's self-injection locking microcomb to user chips' injection-locking lasers, and phase tracking in the fibre channels. 1), The self-injection locking microcombs exhibit exceptional stability and superior performance. 2), The local slave lasers, phase-locked with the microcombs through injection-locking, also show high resilience to perturbations commonly encountered in standard monolithic devices, such as those induced by back-scattering to the DBR lasers. In addition, fluctuations in seed light intensity can be effectively re-stabilised at the user chips³⁰, with minimal impact on laser output intensity. Phase-locking of server's microcomb lasers and clients' slave lasers refers to the suppression of phase noises, which are characterised by frequency noises spectra and linewidths, as reported in Fig. 2 of the main text. 3), In quantum channels connecting the server node and client nodes, our streamlined approach that combines dual- λ methods and microcomb-enabled coherent WDM techniques (see the above paragraph), simplifies phase tracking and locking by obviating the need for intricate electronic controls, redundant ultra-stable cavities, and complicated phase controls in the channels. The microcomb-driven integrated photonic devices enable reliable transmission across WDM quantum channels, thereby providing an efficient solution for multi-wavelength, multi-user and long-haul TF-QKD networks.

Technical aspects and protocol implementation:

In the experiment, a short fibre is used between the server and client nodes: what is the power of each comb line after filtering? Is the choice of a short servo fibre motivated by technical limitations? For example, for a 185 km servo fibre, the EDFA would need to compensate for nearly 40 dB loss: is it feasible to amplify the comb lines sufficiently without introducing too much ASE and degrade the OIL performance? Would the experiment still work with 185 km of fibre between the microcomb and the client chips, and if not, what would be the limitation?

We thank the referee for insightfully pointing out the necessity and importance of characterising TF QKD with comparable downstream and upstream fibre lengths. In our previous experiment, we intentionally adopted a short downstream fibre for simplifying the proof-of-principle demonstration of TF-QKD network, rather than technical limitations. The power of each comb line after filtering and equalisation was about -15 dBm per line,

which was sufficient for low-noise optical amplification to ensure a minimum of -20 dBm on-chip power of the seed light, in our previous experiment with a short servo fibre.

We fully agree with the referee that in future practical applications, such a balanced TF-QKD network structure with both long upstream/downstream fibres is unavoidable, although our current work aims for a proof-of-principle demonstration. We also agree with the referee that in the more balanced upstream/downstream TF-QKD scenario, some impacts of using long downstream fibres have to be considered, including: (i) attenuation of downstream light intensity, requiring additional EDFA amplifications of comb lines which could introduce ASE and degrade the optical injection-locking (OIL) performance. (2) long optical path in the giant closed-loop MZI results in accelerated phase shifts accumulation in the fibre, (3) Raman and scattering noises.

As suggested by the referee, **we have now implemented several new experiments with long downstream fibres.** Limited by experimental resources in our lab, we used upto 120 km-long downstream servo fibre, not that long, but it is sufficient to test noises, OIL phase tracking, and QKD performance. The upstream fibre length was maintained as 370 km (185 + 185 km), while the downstream fibre was extended to 120 km (60 + 60 km) for implementing TF-QKD.

These new experiments were implemented and have now been added to the revised manuscript:

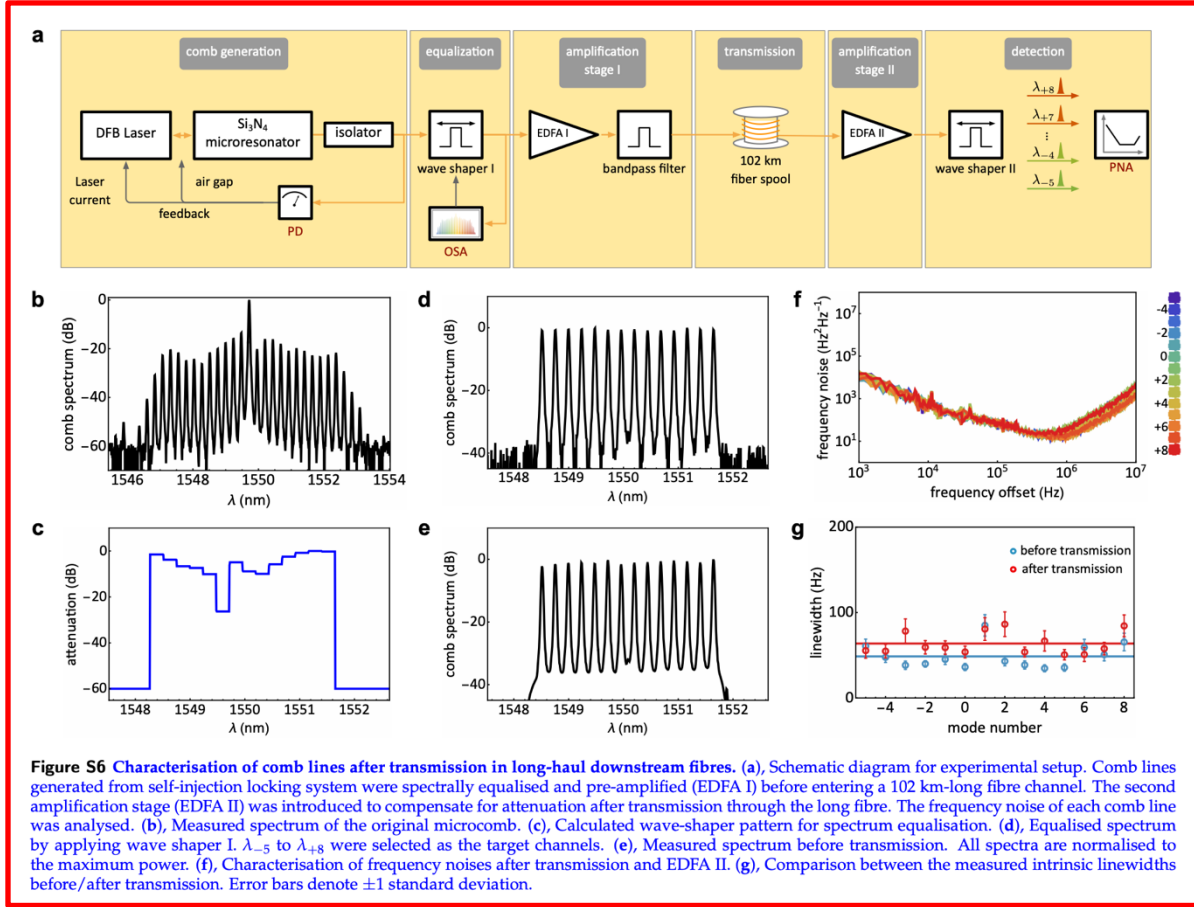
(i) full classical characterisations of local OIL lasers' frequency noise, when all microcomb lines seeding light were sent through long 102 km servo downstream fibres and reamplified by EDFAs. There was no obvious performance degradation observed for all 13 wavelength channels. Excess noise added by ASE of EDFA and Raman effect in the long downstream fibres can be effectively suppressed by introducing additional optical filters before entering the client chips. **These results are reported in the new Fig.S6. These results show nearly the same linewidth before/after transmission through the channel for all 13 wavelength channels (Fig.S6g).**

We have added a new Supplementary Section 5.1 "Network with symmetric upstream-downstream channels". All details of characterisations of local OIL lasers' frequency noises through 102 km fibres have been provided.

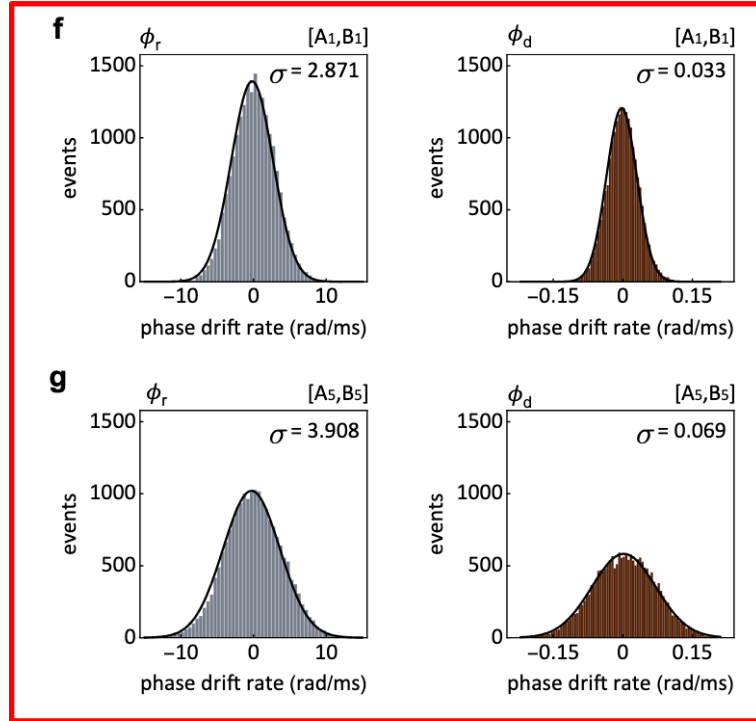
5.1 Network with symmetric upstream-downstream channels

In this section, we present TF-QKD with extended fibre lengths for both the downstream (server-to-client) and upstream (client-to-server) channels. As a proof-of-principle test, we implemented a 102 km downstream fibre link. This introduces approximately 20 dB attenuation of the comb lines, necessitating amplification to maintain sufficient optical power for injection locking at client chips. The amplification process introduces several noise sources that may degrade system performance, including ASE from EDFAs, phase fluctuations induced by long-haul transmission, and nonlinear effects. To characterise the system performance, we constructed the experimental setup shown in Fig.S6a. The generated microcomb first underwent spectral equalisation via a programmable filter (wave shaper I) to normalise power across all wavelength channels (Figs. S6b-d), ensuring uniform gain and SNR for each comb line (λ_{-5} to λ_{+8}). The attenuation pattern uploaded to the wave shaper I was calculated in Fig. S6c. Pre-transmission amplification (EDFA I) was carried out to ensure sufficient input power for the second stage amplification after long fibre transmission (-40 dBm minimum input power per comb line required for low-noise amplification) while maintaining total fibre input below 0 dBm (-11 dBm per comb line) to suppress nonlinear effects. A bandpass filter (about 450 GHz) reduced ASE noise before fibre transmission (Fig. S6e). After post-transmission amplification (EDFA II), we analysed individual comb lines via wave shaper II filtering. The power spectral densities (Fig. S6f) confirm preserved low-noise characteristics across all channels. Comparative linewidth measurements before/after transmission (Fig. S6g) show only minor degradation, attributable to slight SNR reduction. These results verify that proper power management and filtering can maintain comb line quality despite two-stage amplification.

Notably, EDFA-based downstream amplification is well-established in TF-QKD implementations^{20,49,75}. The remaining consideration for extended downstream fibres is additional phase noise. Since the optical injection-locking at the client nodes nearly perfectly replicates the frequency and phase of the seed light, when the upstream and downstream channels are equal in length, the entire process can be considered equivalent to a larger-scale MZI with each arm length doubled compared to the original configuration. Notably, phase tracking remains feasible even for fibre spans exceeding 1,000 kilometres²⁰. Furthermore, in field deployments, it may benefit from partial noise cancellation due to uncorrelated environmental perturbations e.g., vibration and temperature fluctuations) along extended fibres^{19,77}. Consequently, extending the downstream fibre channel is not expected to impose additional challenges for phase tracking. Our experimental implementation (as reported in Figs.3-4, main text) successfully demonstrates efficient phase tracking and SNS-TF-QKD in this symmetric long-haul configuration, validating the feasibility of balanced upstream-downstream quantum communication.



(ii) full quantum characterisation of phase tracking and TF-QKD between two InP client chips (indicated by {A5, B5}, as an example) with 60+60 km downstream fibres, where dual- λ microcomb lines seeding light were sent through two 60 km downstream fibres, amplified by EDFAs and injected into two local InP lasers. **These new results in Fig.3g in the revised main text show a similar phase drift rate** in 120 km long fibres and short fibres, which verifies the effectiveness of OIL on the local InP chips, and more importantly, validates phase tracking in TF-QKD systems with long upstream/downstream fibres. Note that slightly faster phase shifts in the long channel could be effectively tracked by adjusting the relative phase recalibration period in this case (5 ms out of 20 ms $\rightarrow$ 2 ms out of 5 ms). **In the new Fig.4, we also measured the QBER and secure keys for the network employing short and long downstream fibres. These results in the updated Fig.4 imply similar performances of QBER and secured keys by using the short and long fibres.**



In the Fig.3 caption, we have now added: *"The fibre network employed 370 km upstream (185+185 km) and predominantly short downstream links, except for the {A5, B5} paired QKD which adopted 120 km downstream fibres. Phase information was extracted via SNSPD-based single-photon interference measurements (10 kHz sampling rate). Data were collected sequentially for each pairwise connected QKD chips at their wavelength channel, while maintaining continuous operation of all other wavelength channels multiplexed in the same fibres. (e). An example of phase distributions for the {A1, B1} paired QKD chips. Inset: zoom-in view of the initial 100 ms window. (f) and (g), Measured phase drift rate: (f) $\Phi_r = 2.871$ rad/ms and $\Phi_d = 0.033$ rad/ms for short downstream links {A1, B1}, and (g) $\Phi_r = 3.908$ rad/ms and $\Phi_d = 0.069$ rad/ms for long downstream links {A5, B5}. These results verify effective injection locking on local QKD chips and robust phase tracking in TF-QKD systems, with long-haul upstream and downstream fibres"*

In the Fig.4 caption, we have now added: *"(b) and (d), Segmented QBER in the X-basis and their statistical distributions in the 370 km upstream channels. Each data point represents the error rate measured by sending a total of 150×10^6 bins. The network employed short downstream fibres, except for the {A5, B5} with 120 km downstream fibres."*

In the revised main text page 6, we have added: *"For experimental simplicity, short downstream fibres were used in above measurement, except for the {A5, B5} user pair where 120 km (60 + 60 km) fibres were used to characterise the network with realistic long downstream fibres. We characterised injection locking and frequency noise, when combs were transmitted through long downstream fibres and consecutively reamplified (see Fig.S6), achieving comparable performance to short-haul configurations. In Figs. 3f,3g, comparative results reveal accelerated phase drift in long downstream fibres (see ϕ_d, ϕ_r for {A1, B1} and {A5, B5}). This behaviour emerges from the formation of a giant interferometer, where injection-locked lasers replicate the seed light's phase information. Despite increased drift, phase tracking can be achieved by simple adjustment of phase correction"*

cycles as the following: Φ_d was recalibrated every 2 ms (5 ms cycle) for {A5, B5} versus every 5 ms (20 ms cycle) for other pairs."

In the Supplementary information Section 4 "WDMed Quantum channels in fibres", we have added more details:

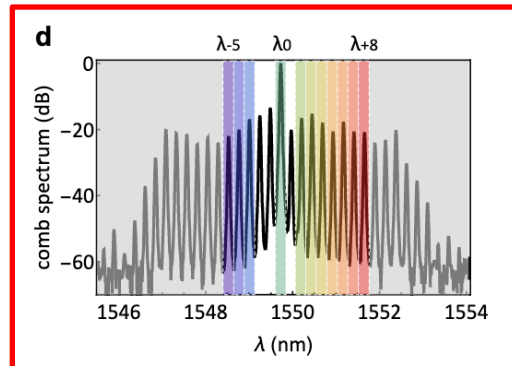
WDMed Quantum channels in fibres: The reference and quantum signals were wavelength-multiplexed and transmitted in the long-haul upstream fibre spool back to the server node simultaneously. The upstream channel distance from Alices' and Bobs' node to the central server node and corresponding fibre losses are provided in Table S3. Constrained by limited RF resources, we simulated concurrent multi-user communication by implementing the whole quantum state encoding procedure in sequence for the selected user pair while leaving other non-target wavelength signals unmodulated and directly injecting into the upstream fibre channels. To evaluate worst-case crosstalk, these non-target wavelength signals were maintained at maximum intensity levels required for phase tracking (see Section 4.3). To simplify the system for a proof-of-principle demonstration of TF-QKD network, the downstream fibres from the microcomb to the QKD client-chips were replaced by short fibres in most cases, except for the user pair {A₅, B₅}, where 120 km-length (60+60 km) downstream fibres were used. We confirm comparable phase drift and phase tracking for short and long downstream fibres in Fig.3 and implement TF-QKD in both cases in Fig.4. Detailed performance characterisation regarding the introduction of long downstream fibres is presented in the main text and further discussed in Section 5.1.

The comb lines are split by 30.03 GHz, but this doesn't align with ITU channels as opposed to what is stated in the introduction. Which ITU channels were used for each pair of clients and how did the authors mitigate deviations from the ITU grid?

In the current experiment, we used a microcomb with an FSR of 30.03 GHz, as the referee correctly pointed out, the comb line spacing doesn't match the standard ITU channel spacing. We have removed the statement of ITU compatibility in the introduction and in the conclusion, to avoid any misleading. In the revised main text Page 4, we have clarified that the microcomb with a 30.03 GHz spacing was used in our experiment:

We emphasise several unique capabilities of integrated-photonics QKD networks. i, ultra-low-noise coherent dark-pulse microcombs provide ultra-low-noise lasers required for TF-QKD and establish a globally-stable phase reference for the entire network. ii, high-yield fabrication and operation of QKD transmitter chips are key to ensure high QKD performance, critically advancing the scalability of quantum networks. iii, broadband and equally spaced comb lines (with intervals adjustable to International Telecommunication Union standards) can facilitate massive wavelength-multiplexed QKD between a large number of client chips (in current experiments we adopted a 30-GHz spacing for proof-of-concept demonstration).

In our original experiments, QKD experiment was implemented sequentially between pairwise users (the same two InP chips) at distinct wavelengths. In the new TF network, we implemented QKD experiments with 20 InP chips and 11 wavelengths copropagating in parallel through the fibres. The same wavelength channels with a 30.03 GHz spacing were chosen as those near the reference light (we have modified the Fig.2d to better view the chosen wavelength).



The main difference between old and new experiments is the filtering processes. In the old experiments, merely necessitated spectral separation between the quantum and reference signals. We implemented a compromised filtering strategy by considering the relationships of $2\times$, $3\times$, and $5\times$ of 30.03 GHz just fall within the spectral passband of standard 50 GHz ITU grid channels, where commercial WDM filters exhibit sufficient bandwidth to accommodate slight spectral offsets from nominal centre wavelengths. In the new experiments, we used a customised optical filter to (de)multiplex those wavelengths using fibre Bragg gratings (~ 0.08 nm bandwidth), which exhibit low insertion loss (~ 1 dB), single-stage filtering depth of 30 dB (cascading two will achieve 60 dB). These filtering data have been provided in a new Tab.S3 and we have added these details in Supplementary Section 4.1 "Single-photon detection at the server node":

Single-photon detection at the server node: The demultiplexed signals were routed into pairs to implement the dual- λ phase tracking. Fibre Bragg grating filters (with a 0.08 nm bandwidth) were used to segregate the reference and quantum signals, exhibiting low insertion loss (about 1 dB each), and single-stage filtering depth of 30 dB (cascading two Bragg filters will achieve 60 dB), see Table S3. To simplify the client

A_1-A_{10}	channel length (km)	102.53	185.131
	fibre loss (dB)	19.70 ± 0.03	34.49 ± 0.02
B_1-B_{10}	channel length (km)	102.708	185.299
	fibre loss (dB)	20.22 ± 0.02	35.11 ± 0.03

user	A_1-A_3	A_4-A_6	A_7-A_{10}
filter loss (dB)	1.86 ± 0.01	1.75 ± 0.01	1.66 ± 0.01
user	B_1-B_3	B_4-B_6	B_7-B_{10}
filter loss (dB)	1.85 ± 0.01	1.90 ± 0.01	1.59 ± 0.02

Table S3 Loss characterisations of fibre channels and optical filters used in the network. Each set of fibre Bragg grating filters was thermally tuned to align with specific QKD pair wavelengths. The total insertion loss accounts for both cascaded Bragg filters and fibre optical circulators. Channel lengths are based on manufacturer specifications, while losses were experimentally characterised through 10 repeated measurements to determine mean values and standard deviations.

Moreover, we also would like to emphasise that a fully-ITU matched network is readily achievable by using an existing microcomb device with 50/100 GHz FSR matching standard ITU channel spacing [e.g, Science373,99-103(2021)]. This will enable full compatibility with standard telecommunication instruments, thereby facilitating more cost-effective deployment in practical real-field quantum communication networks.

We have now added this in Supplementary Section 4.1 "Dark-pulse microcomb generation at the server chip".

The spacing between different wavelength channels was 30.03 GHz (equal to the FSR of the microresonator), misaligning with the standard ITU channel spacing. Integrated microcombs matching standard ITU channel spacing (e.g., 50/100 GHz) can be readily implemented⁷², enabling full utilisation of mature WDM components for wavelength allocation and spectral filtering. This could facilitate cost-effective deployment in real-field quantum communication networks. After the comb line assignment based on network configuration, polarisation

How critical is the temperature stabilization of the micro-ring chip and how does the comb-line drift over time? Is the microcomb chip only stabilized by temperature? Is it locked to the HCN cell? If not, how stable is it in time?

Both micro-ring and DFB pump chips that used in the self-injection-locking dark pulse generation, were temperature stabilised using a temperature controller with a 1 mK precision and 4 mK stability. We captured the comb spectrum every minute over 12 hours using an optical spectrum analyser (MS9740A, Anritsu), and the results are shown in Fig.2e. This result indicates negligible drift of the comb lines. In the revised manuscript, we have now added the relative intensity fluctuation plot in a new Fig.2f to provide a clearer characterisation of the stability. A mean value of 0.994 ± 0.006 in 12 hours denoted that the microcomb retained the steady state, highlighting the stability of the system. The microcomb was monitored with the output power and the feedback signal was used to control the DFB's current and the air gap between the laser chip and micro-ring chip, which has been provided in Fig.S3. We also would like to emphasise that in the large MZI configuration implemented in the TF network, long-term absolute wavelength stability of the comb lines has a negligible impact on the

interference outcome. Instead, the interference visibility is primarily determined by the short-term phase stability of the lasers—specifically, the linewidths of the comb lasers as well as local lasers on the InP chips. This allows us to implement the TF-QKD network with high stability without locking to the HCN gas cells. We have added a detailed description of the stability measurement in the caption of Fig.2.

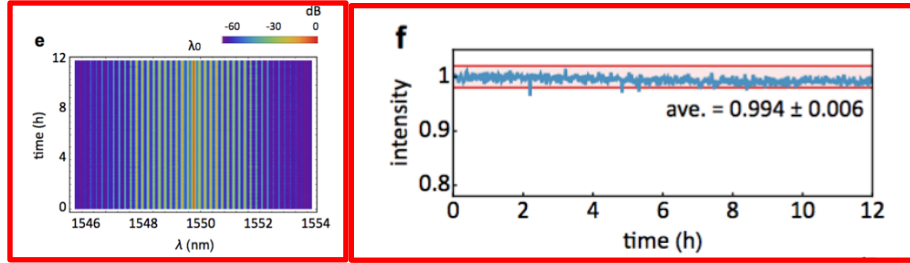
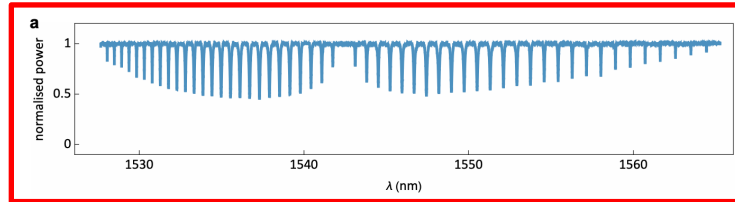


Figure 2...(e) and (f), Spectral stability characterisation of microcomb. The microcomb's spectrum was collected every minute with an optical spectrum analyser over consecutive 12 hours. The normalised intensity fluctuation (f) extracted from (e) shows excellent system stability maintaining a mean relative intensity of 0.994 ± 0.006 .

Moreover, though the HCN gas cell was not used for stabilisation of the microcomb, the HCN cell was used for calibration of the microresonator's transmission spectrum. We have added the description of the HCN gas cell in revised Supplementary Section 1: "(2) a 16.5 cm fibre-coupled hydrogen cyanide (HCN) gas cell maintained at 100 Torr pressure with C-band absorption peaks serving as an absolute frequency reference (peak wavelength uncertainties on the order of 0.1 pm, see the measured absorption spectrum in Fig.S1a)", and added the measured absorption spectrum of HCN in a new Fig.S1a.



There is no mention of the number of added phases used at Alice (Bob) for key encoding and phase randomization. Can the authors describe how this was implemented?

We have added the detailed description of key encoding and phase randomisation in Supplementary Section 4.1 "Quantum keys encoding at the InP client chips". We have also added a new Supplementary Section 4.2 to discuss how to implement phase randomisation.

4.2 Phase randomisation for implementing the decoy state method

Phase randomisation is essential for the decoy state method using weak coherent state sources. In the experiment, the random encoded phase $\delta_{A(B)}$ was set by applying a sawtooth voltage on the phase modulator at the client chip, sweeping from 0 to 2π at one quantum key encoding stage (that is, successive 15 ms in the period of 20 ms). Given the system repetition frequency of 200 MHz, an equivalent discrete randomisation level of 3 million was reached. For a proof-of-principle experiment, the preset repeated phase sequence effectively emulates the random phase settings⁷⁴. The random phase and the encoding phase always work as a whole. We can consider the sawtooth voltage as providing phase randomisation and encoding phase at the same time, which would not affect the result while simplifying the implementation. Statistically, it is equivalent to standard methods that apply random sequences of discrete phase levels as required in decoy states and practical QKD. In the actual QKD scene, it is necessary to use a truly random phase sequence to avoid malicious attack by successfully guessing the phase randomisation information, but a simple phase sweeping across 2π phase range would still yield a proper estimation⁷⁴. Moreover, in our current experiment, the level of phase randomisation was characterised by SNSPD photon counting for simplicity. In practical cases, an intensity monitor photodiode can be added to confirm the decoy state intensity before attenuation to a single photon level, which could be done by the integrated photodiodes on our chip.

The quantum bit error rates in the Z and X bases are not given, nor discussed. Can the authors report these values in a table?

We thank the referee for the suggestion. We presented the quantum bit error rates (QBER) in the X basis in the new Fig.4 in the main text: Fig.4a and Fig.4b report segmented QBER in the X-basis in the 204/370 km case; Fig.4c and Fig.4d report their statistical distribution.

The X-basis QBER provides a complete performance metric for the entire network, reflecting the microcomb source's stability at the server node, injection locking and state encoding at QKD client nodes, phase tracking across the fibre channel, and single-photon detection at the server node. These phase-sensitive X-basis results have verified successful twin-field generation between distant InP chips. In our implementation of the SNS-TF-QKD protocol, where the bits were encoded in the Z basis according to the choice of sending or not-sending by the users, the Z-basis QBER is primarily determined by the sending probability and detector accidental counts.

As the referee suggested, for the 20-chip TF-QKD network linked via 10 WDMed channels, a full set of QBER in the Z and X bases has been provided in Tab. S5. For the old 2-chip TF-QKD network linked via 10 WDMed channels, QBER in the X basis has been removed to Supplementary Information and provided in Fig.S8, and a full set of QBER in the Z and X bases has been provided in Tab. S6.

Long fibres tend to expand with temperature, causing fluctuations in the time of flight that can reach hundreds of ps. Did the authors observe photon arrival time drifts over the long fibre links and how was that addressed for the different client pairs?

We thank the referee for pointing out the necessity of analysing fluctuations in the temporal delay of light in long fibres under temperature variations, so as fluctuations in polarisation of light. We have now implemented experimental characterisation of these drifts within 6 hours and these results have been provided in the revised manuscript (Fig.S4).

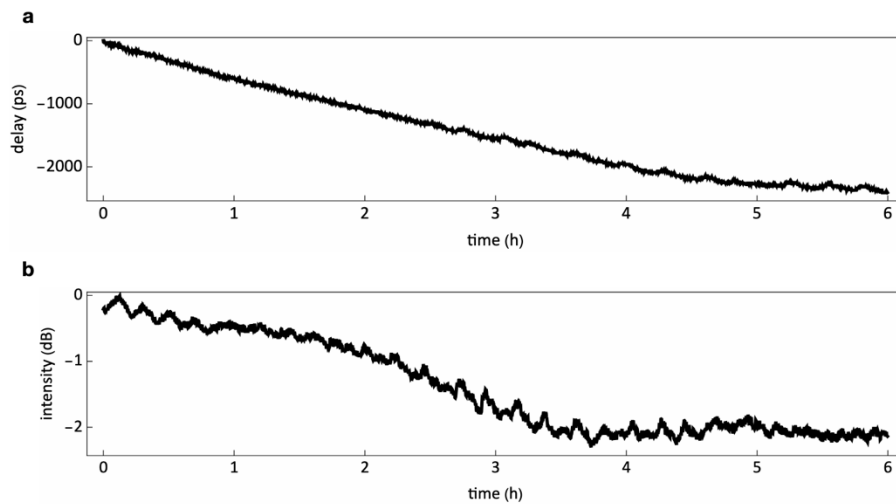


Figure S4 Characterisation of temporal delay drift and polarisation drift. (a) and (b), Delay and polarisation drift tests in the 185 km fibre channel. Data points were acquired at 10-second intervals for both parameters, with each condition measured independently to ensure accurate characterisation.

In our experimental implementation, we employed an automated active stabilisation system to compensate for temporal delay drift. This system continuously monitored both the intensity and interference visibility of quantum signals during the phase tracking period, dynamically adjusting the electrical driving signal delays. For polarisation drift compensation, we utilised slow-axis-aligned polarisation-maintaining beamsplitters at the server node, combined with manual adjustments using fibre polarisation controllers for each QKD user. Independent monitoring and compensation of temporal and polarisation parameters enable full stabilisation procedures across each paired QKD users. **We have now provided these details in Supplementary Section 4.1.**

We emphasise that achieving high interference visibility at the server node requires identical light fields across all degrees of freedom. Transmission through long fibre channels introduces temporal delays and polarisation drifts, primarily due to environmental temperature fluctuations. Our measurements of the 185 km fibre channel, as reported in Fig.S4, revealed time-dependent variations in both delay and polarisation. In this work, polarisation-maintaining, slow-axis-aligned 50:50 beamsplitters were employed at the server node. Realignment was performed by monitoring both the quantum signals' average intensities and interference visibility during the phase tracking period. In the experiment, while temporal delays were automatically compensated by adjusting the electrical driving signal timing, polarisation required manual realignment every 10-20 minutes (which could readily be overcome through the use of automated polarisation controllers with real-time compensation capabilities).

Other:

In the literature review, the authors include prior work related to chip-based MDI-QKD, however they seem to have missed a more recent work on chip-based TF-QKD, also implementing optical injection locking and phase encoding on chip. This reference should be added for completeness.

We are grateful to the referee for highlighting the significant work by Toshiba on chip-based TF-QKD (Optica 10, 1385-1390, 2024), which we inadvertently omitted in our original submission. We have now incorporated this reference **in the revised manuscript Page 4**, with a discussion of its relationship to our findings. Should this not be the specific study the referee mentioned, we would appreciate further clarification to ensure we address all relevant prior work appropriately.

with the specific emphasis on practical QKD applications³². Previously, protocols of prepare-and-measure QKD^{33–39}, MDI-QKD^{40–43}, and entanglement-based QKD^{14,44–46} have been implemented with integrated photonic devices, but primarily in the point-to-point scenario. Remarkably, chip-based point-to-point TF-QKD by using partially integrated InP photonic chips was demonstrated⁴⁷.

Page 6: "Infinite-size effects" should be rephrased "finite-size effects".

We thank the referee for their meticulous review. The typo has now been corrected, and we have performed careful checks throughout the revised manuscript to ensure accuracy.

Table S5 isn't mentioned in the main text or supplementary material.

We appreciate the reviewer's careful attention to detail in noting this omission. We have now added an explicit cross-reference to Table S5 (**main text Page 7**) to guide readers to the complete QKD dataset: **"Full experimental data across all 20 client-chips, including gain and Z/X-basis QBER, are summarised in Tab. S5."** The table contains the full experimental parameters and performance metrics referenced in our analysis.

We believe all of the referee's concerns have been thoroughly addressed both in this response letter and in the revised manuscript. We are deeply grateful for the referee's insightful and constructive comments, which have been very instrumental in helping us significantly improve our work. The thoughtful feedback has significantly strengthened both the technical rigour and clarity of our manuscript.

Referee #2 (Remarks to the Author):

In their paper, Zheng et al. reports a very nice demonstration of the possibility of using a microcomb-driven integrated photonic QKD network that exploits Twin Field QKD, a technology that allows, in principle, to increase the distance of key transmission at a reasonable rate.

While the proposed article is undoubtedly of high impact for the quantum communication community, I do not believe it holds the same level of significance for a broader audience. The existence of star networks for QKD is not a novelty, the Twin Field protocol is well known, and the dual-band system for phase noise stabilization in optical fibers has already been widely demonstrated so this paper brilliantly overcomes the technological challenge of stabilizing multiple Twin Field setups simultaneously. However, in itself, I do not believe a general audience would appreciate this technological advancement as much as a more specialized readership would. Moreover, the paper is written in a rather technical way which makes it unsuitable for a wide audience.

For this reason, I don't recommend the publication in Nature but the resubmission to a more specialistic journal.

We are deeply grateful to the referee for their time, expertise, and thoughtful review of our manuscript. Their insightful and constructive comments have been invaluable in improving our work. In the revised manuscript, we have carefully addressed all the referee's comments and suggestions. We particularly appreciate the referee's highly constructive feedback regarding the necessity of clarifying **dual-band techniques in TF-QKD**. We have provided a detailed clarification in our response letter and revised the manuscript accordingly. We sincerely believe that the referee's suggestions and comments have greatly enhanced the clarity and rigour of our manuscript, and we are thankful for the opportunity to strengthen our work.

We agree with the referee that key technologies for point-to-point long-distance TF-QKD systems — including star network architectures, twin-field protocols, and dual-band systems - have been well-established in non-integrated photonic systems where the users are realised in standard optical fibre and bulk optic systems.

The main innovation of our work lies in the first experimental realisation of TF-QKD networks using integrated photonics, demonstrating that our developed integrated photonic devices (including client-side QKD transmitter chips and server-side microcomb chips) can support large-scale, mass-user, long-haul TF-QKD networks. This achievement primarily establishes the scalability of integrated photonic devices for large-scale quantum networking, rather than focusing on the development of new protocols or architectures or dual-band techniques — though we emphasise that our integrated QKD devices remain fully compatible with these existing architectures/protocols/technologies, which further enhance the scalability and practicality of QKD networks.

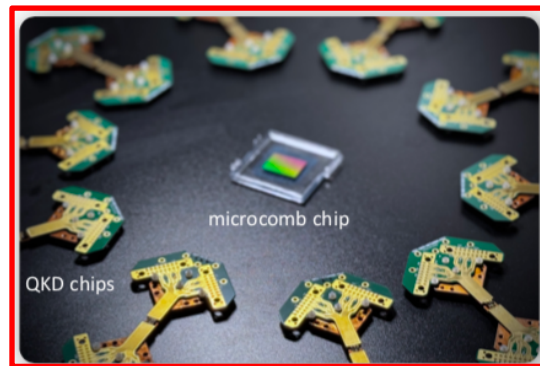


Fig.1c: A large-scale TF-QKD network with 20 QKD transmitter client-chips and a server-side microcomb chip.

This work represents significant advancements to TF QKD network technology through three key dimensions: (1) device-level innovation: fully integrated QKD devices with high performance, high reproductivity, and high scalability, (2) system-level advancements: the first TF-QKD network demonstration, and (3) strong scalability and practicality for mass-user and long-haul QKD networks.

(1) Integrated photonic device-level innovation (fully integrated QKD devices with high performance, high reproductivity, and high scalability)

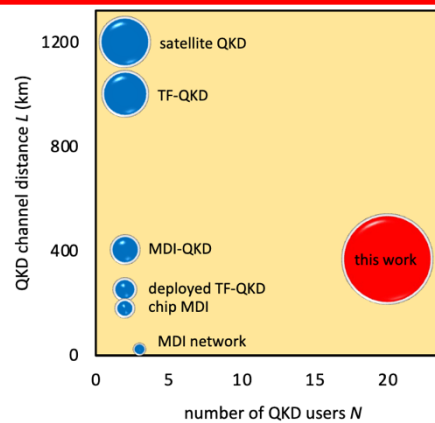
- InP-based QKD transmitter chips at the client node, integrating all critical functions for TF-QKD:
 - weak coherent state regeneration (for ultralow noise lasers)
 - pulsation and intensity modulation (for decoy states)
 - phase modulation (randomisation and key encoding)
- Integrated high-performance SiN microcomb chip at the server node:
 - Hz-level ultra-low noise
 - ultra-high coherence
 - broadband wavelength multiplexing capability
- Our integrated photonic device features:
 - 20 copies of InP QKD chips fabricated on a single 3-inch wafer
 - high performance, high reproductivity, and high scalability across all components on the client chip
 - these integrated devices remain compatible with WDM parallel QKD technologies
 - these integrated devices remain compatible with TF-QKD architectures/protocols/technologies

We would like to mark a few points: conventional integrated quantum photonic chips typically faced challenges in realising TF-QKD transmitter client-chips due to fundamental technical hurdles. Our work overcomes these limitations through key advancements: full integration of critical components in particular Hz-level linewidth lasers (key for TF-QKD) and unprecedented scalability (key for QKD networking), including massively parallel low-noise laser arrays, native WDM compatibility and uniform performance across all InP client-chips. This represents the first demonstration of QKD chips with all capabilities essential for scalable networks — all in a manufacturable photonic integrated circuit. In the original manuscript: the TF QKD network was implemented with 2 InP QKD transmitter chips by switching 10 different waveguide channels. In order to further strengthen our demonstration of the first TF-QKD network with strong scalability of many-user and long-haul networking, in the revised manuscript, we have reimplemented the **entire TF-QKD network with 20 TF-QKD chips** (see new Fig. 1c) and have recollected nearly all experimental data in Fig.2 and all data in Fig.3 and Fig.4 of the main text, Extended Data Fig.1, along with additional data in Supplementary. Moreover, to assess the system's adaptability to more practical networking configuration, we have implemented TF-QKD between two InP chips with long-haul downstream and upstream fibres, and these new results have been included in Fig.3 and Fig.4. The comprehensive characterisation of all InP client-chips in Fig.2 confirms the high yield and reproducibility of integrated lasers and modulators, **underscoring their strong scalability for large-scale QKD networks**. To our knowledge, **this level of concurrent operation across multiple quantum communication chips has never been demonstrated**. For TF-QKD, there has scarcely been achieved even between two point-to-point users with fully integrated photonic chips (with the exception of a *partial* integration in *Optica* 10, 1385–1390 (2024) by Toshiba, published during the preparation of our work and has been cited now).

(2). System-level advancements: demonstration of the first TF QKD network with integrated photonics

- [demonstration of the first TF-QKD network](#)
- [network with 20 client chips and 370 km between paired chips \(overcoming the repeaterless bound\)](#)
- [demonstration of the largest-scale networking capability \(3700 km\) to date, with no trusted relays](#)
- [demonstration of a quantum leap in QKD network's scalability, surpassing all previous implementations \(including Toshiba's latest 2-user deployed TF-QKD network in ref. Nature 640, 911-917 \(2025\) published during our review\)](#)

We would like to mark a few points: while the development of global-scale quantum communication networks has demonstrated milestone implementations, including space-to-ground [Nature 589, 214-219 (2021)] and microsatellite-based networks [Nature 640, 47-54 (2025)] — these systems rely on trusted-node architectures. **Their long-standing objective has been to integrate protocols based on untrusted nodes into network architectures.** A summary of state-of-the-art QKD and networks (originally in Fig. 5 and now relocated to Extended Data Fig. 2) highlights the impact and contribution of this work. **By leveraging integrated photonic technologies, we have realised the first TF-QKD network and demonstrated exceptional scalability for mass-user and long-haul QKD (which has been many years/decades pursued in the quantum cryptography and quantum communication field).** We fully acknowledge the referee's insightful observation of TF-QKD's potential for star-network architectures. While theoretical studies have indeed identified these advantages, their experimental realisation has remained elusive due to fundamental device-level challenges. Our work here addresses this implementation gap. Notably, during our review process, Toshiba (the team that originally proposed the TF-QKD protocol [Nature 557, 400-403 (2018)]), reported the TF-QKD implementation in deployed fibre networks [Nature 640, 911-917 (2025)]. Their remarkable demonstration still remained limited to two point-to-point users using bulk optical systems, while it directly highlights the challenges and significance of scaling TF-QKD networks. Our work overcomes these challenges through integrated photonic devices, demonstrating for the first time a TF-QKD network that simultaneously achieves scaling to 20 users and operation over long distances.



Extended Data Fig. 2 Summary of state-of-the-art QKD and QKD networks without trusted intermediate nodes. The size of points in the visualisation represents the total quantum networking capability. In the TF-QKD network presented in this work, we achieved a total quantum networking capability of $NL/2 = 3,700$ km, with $N = 20$ chip-based QKD users and $L = 370$ km channel distance. Some notable demonstrations of QKD and QKD networks include: the longest satellite-based QKD in ref.[61]; the longest fibre-based TF-QKD in ref.[20]; deployed TF-QKD in ref.[22]; the longest MDI-QKD in ref.[62]; longest chip-based MDI QKD in ref.[42]; a three-user MDI-QKD network in ref.[63]. Results from QKD networks relying on trusted intermediate nodes are excluded from this summary.

(3). Strong scalability and practicality towards large-scale integrated-photonic QKD networks

- [high yield, high uniformity and high reproducibility of InP QKD transmitter chips at the client nodes](#)
- [Hz-level, coherent, broadband wavelength multiplexing capabilities of microcomb at the server node](#)
- [both transmitter chips and microcombs allow massive-user parallel QKD in the network](#)
- [the communication distance between two user chips can be scaled to 1000 km, by using low-noise SNSPDs](#)
- mass manufacturability at the client node and cost-sharing advantages at the central server node, resulting in [an entirely cost-efficient quantum network](#)

We mark that the TF-QKD offers the additional advantage of enabling resource sharing — where multiple cost-effective user nodes can utilise expensive centralised infrastructure. This architecture is particularly enabled by our mass-manufacturable, highly identical TF-QKD photonic chips, which provide the critical technological foundation for scalable implementation of long-distance, multi-user quantum networks.

In summary, building upon the three key technological advancements and their significance discussed above, our work represents a paradigm shift from point-to-point to scalable QKD networks, achieving the first many-user, long-distance TF-QKD network implementation. This work demonstrates the transformative potential of integrated quantum photonics through its unique combination of chip-scale miniaturisation, cost-effective and massive manufacturing, strong scalability, along with its compatibility with scalable WDM TF-QKD architecture. Together, these advances can address the fundamental challenges hindering large-scale quantum networks.

Interdisciplinary impacts and significance: Beyond the technological advancements and the significance of realising an integrated-photonic TF-QKD network, this work represents a pivotal convergence of cutting-edge technologies, including integrated quantum photonics, integrated optical frequency microcombs, and quantum communication networks. For the **integrated photonics community**, we here resolve the critical scalability challenge of quantum communication networks with manufacturable integrated systems. In particular, our implementation of microcomb technology, inventively studied for classical photonic applications, now creates new opportunities in quantum information science. For the **quantum communication community**, we bridge the gap between laboratory proofs-of-concept and future large-scale field-deployable systems through chip-scale miniaturisation enabling robust operation, foundry-compatible components for massive production, and WDM-parallel transmissions. For the more **broad scientific community**, we show how the interdisciplinary collaboration of quantum physics, photonic engineering, and material science can produce tangible advances in quantum information technologies. We therefore believe this work's interdisciplinary nature aligns well with *Nature's* broad scientific scope and will appeal to its wide readership across physics, engineering, and materials science.

Following the referee's comment and suggestion on the technological advancements and representation of our work, we have revised the manuscript to avoid potential misinterpretations about improvements to network architectures, TF protocols, and dual-lambda systems, while clarifying that our main focus is on demonstrating the first integrated-photonic TF-QKD system and its scalability. **We have particularly modified the Abstract and Introduction to better represent these aspects for *Nature's* broad readership.**

Revised Abstract and Introduction:

Quantum key distribution (QKD) leverages the principles of quantum mechanics to enable provably secure communication^{1,2}. One significant challenge persists in the development of large-scale QKD networks with a large number of clients over long communication-distances^{3,4}. While quantum relays continue to pose practical difficulties⁵, existing trusted node networks^{6–10}, point-to-multipoint networks^{11,12}, and wavelength-multiplexed entanglement networks^{13,14}, encounter issues such as reliance on trusted intermediaries or limited distances. Twin-field (TF)-QKD provides a compelling architecture that can overcome those issues while enhancing communication-distance¹⁵. Though long-distance point-to-point TF-QKD have been achieved^{16–22}, realising large-scale network requires scalable quantum devices. Here, we report proof-of-principle demonstration of integrated-photonic TF-QKD network with exceptional scalability and reliability. This network integrates twenty independent client-side QKD transmitter chips with one server-node integrated optical microcomb chip. The microcomb generates a broad spectrum of ultra-low-noise coherent frequency combs with Hertz-level linewidths, which serve as seeds and references for all client-chips. Each chip regenerates ultra-low-noise light phase-locked to microcombs and prepares quantum keys, achieving high performance, identical operation and high scalability through monolithic photonic integration. We sequentially implement pairwise QKD across twenty client-chips through ten wavelength-multiplexed channels, with each surpassing the repeaterless bound at 370 kilometres in spooled fibre, achieving a networking capability (client-pairs $\times$ communication-distance) of 3,700 kilometres. Combining mass-manufacturability, cost-effectiveness and high scalability of integrated photonics with long-distance quantum communication represents a viable path to large-scale quantum networks.

communications^{16–22}. The practical implementation of TF-QKD networks faces substantial technical challenges. These include development of many ultra-low-noise coherent laser sources, mass manufacture of identical, high-performance QKD chips that maintain uniformity across all client nodes, and system-level integration that enables scalable quantum node operation and quantum channel transmission, while remaining compatible with existing phase tracking. They collectively represent the fundamental requirements for TF-QKD network infrastructure, demanding simultaneous advances in photonic integration, manufacturing scalability, and system control.

Here, we present proof-of-principle laboratory demonstration of user-massively-scalable and long-haul TF-QKD network enabled by integrated photonics, named as “Weiming Quantum Chip-Network”. Our integrated-photonic QKD network comprises a central server chip that integrates an optical microresonator frequency comb (microcomb) on silicon nitride (Si₃N₄) platform, and 20 copies of independent client-side QKD transmitter chips that monolithically integrate all essential components for key preparation based on indium phosphide (InP) photonic circuits. These InP QKD client chips, fabricated on a 3-inch wafer, were characterised with identically high performance, reproducibility, and high operational yield, thus providing scalable quantum devices for network implementations. We harness integrated microcomb technology, which has revolutionized classical photonics^{24–26}, to dramatically enhance TF-QKD network’s scalability and reliability by delivering a large number of ultra-low-noise, phase-coherent comb lasers for WDM-based networks across distributed client chips. We implemented the pairwise TF-QKD between 20 InP client chips through 10 wavelength-multiplexed channels aligned with microcomb lines, realising a total network spanning capability $NL/2 = 3700$ km (where $N=20$, $L=370$) without any trusted relays.

Furthermore, while this work presents a proof-of-principle laboratory demonstration, we have also clarified a pathway toward real-world implementation in the revised manuscript. For example, in the revised manuscript, our analysis examines key practical considerations for future TF-QKD networks, including “Global phase tracking with dual- λ method” in Supplementary Section 4.3 (see our response to the referee’s other comments), “Noises in fibre channels” in Supplementary Section 4.4, “Network with symmetric upstream-downstream channels” in Supplementary Section 5.1, “Fully connected and asymmetric QKD networks” in Supplementary Section 5.2, and “Security analysis and discussion” in Supplementary Section 6.

Anyway, there are some points that, in my opinion, authors should consider improving the presentation of their results, in the case of a new submission:

1. The core of the paper is the use of microcombs to allow simultaneous phase tracking by using dual band method in each channel of the network. Anyway, they state that they use postselection instead of phase shift compensation. I'm a rather bit confused: why authors are using a method that is born to stabilize the channel and avoid postselection of data if they do perform postselection? The authors should better explain this point

We sincerely thank the referee for highlighting the need to clarify our dual- λ phase tracking and postselection. **The objective of this study is to establish a proof-of-concept for integrated-photonic TF-QKD networks — with focus on device-level networking scalability, rather than existing channel-level techniques.** Both phase compensation [e.g., Nature Photonics 15, 530–535 (2021), Nature Photonics 16, 154–161 (2022), & Nature Communications 14, 928 (2023)] and postselection [e.g., Phys. Rev. Lett. 123, 100505 (2019), Nature Photonics 15, 570–575 (2021), & Phys. Rev. Lett. 130, 210801 (2023)] — **the record of 1000 km TF-QKD** have been widely implemented in pioneering TF-QKD experiments. **Our implementation here uses dual- λ phase tracking and postselection**, which is sufficient for this demonstration while maintaining the system's simplicity.

Importantly, in the context of key rate, there is no fundamental difference between using postselection or phase compensation. This is because with phase randomisation (that is required for decoy states), valid X11-basis events inherently necessitate postselection (Eq. S16).

$$1 - |\cos[(\delta_A - \delta_B) - (\phi_B - \phi_A)]| \leq |\epsilon_\phi|$$

Eq. S16

These global phases act on the user-encoded optical fields and ultimately determine the long-distance single-photon interference visibility. The ultimate phase interval selection depends on the combined effects of $\{\delta_A, \delta_B, \phi_A, \phi_B\}$. Because the values of randomly chosen $\{\delta_A, \delta_B\}$ in phase randomisation are announced publicly for verification, the difference between (i), real-time compensation of the global phases or (ii), real-time tracking with postselection is whether $\phi_B - \phi_A$ could be regarded as a constant preset value $\Delta(t) = \Delta(0)$ or time-varied known value $\Delta(t)$. Both approaches ensure uniform phase distribution of the total relative phases in $[0, 2\pi)$, because the global phases Δ follow the uniform temporal distribution. Thus, **both phase compensation and postselection** methods make identical proportions of effective events satisfying Eq. S16, with no additional event loss and **no difference in key rate**. However, we fully agree with the referee that for field-deployed QKD systems, phase compensation offers a practical advantage by eliminating the additional data sifting required in postselection approaches. In such implementations, phase compensation methods can be independently applied in fibre channels. **We have added these detailed discussions in Supplementary Section 4.3.**

In the revised manuscript, we have reimplemented the TF-QKD network with 20 TF-QKD chips (in Fig.2, Fig.3 Fig.4). In our experiment, phase tracking was implemented sequentially, pair by pair, so as the QKD between 20 InP chips. This method effectively emulates the simultaneous (global) phase tracking across all wavelength channels which are designed to copropagate between two metropolitan areas in the network. We maintained parallel transmission of all other quantum signals in the same fibre. This configuration has set the worst case of crosstalk and noise photons that may increase QBER, which we have rigorously analysed and experimentally

validated (detailed analysis and experimental results can be found in a revised Supplementary Section 4.1: the "WDMed Quantum channels in fibres" paragraph).

We would like to emphasise that our streamlined approach which combines dual- λ methods and microcomb-enabled coherent WDM can simplify phase tracking, providing an efficient solution for multi-wavelength, multi-user, long-haul TF-QKD networks. In our network configuration in Fig.1d, users within the same metropolitan zone share common upstream/downstream backbone fibres (spanning hundreds of kilometres) connecting the server and intermediate nodes, while requiring dedicated short-reach fibres between client nodes and the intermediate node, resulting in each client-server connection comprising both shared long-haul and short fibre segments. When these dedicated fibres are sufficiently short with slow phase drift rates, metropolitan users can share a common reference wavelength (because of the locked phases between all comb lines generated by the same high-stability microcomb) for phase tracking instead of requiring individual reference wavelengths. Phase postselection implementation announces all reference wavelength phase shifts, enabling neighbouring users to select appropriate phase windows for data sifting. When the dedicated fibres' length becomes excessive, the phase drifts accelerate, necessitating separate reference and quantum wavelengths for each user. For our experimental demonstration under stable laboratory conditions, we employed a common reference wavelength λ_0 with sequential phase tracking for user pairs while maintaining all other quantum signal transmissions (without detection). The statistical characteristics of phase shifts in the fibre spools demonstrated temporal stationarity (see new results in Fig.3), thereby validating this method for evaluating simultaneous phase tracking across all communication channels.

We have added a paragraph in the main text Page 6.

We implemented lab-scale proof-of-principle quantum network of 20 QKD client-chips linked via 10 WDMed channels. Phase tracking and key distribution were sequentially executed between paired chips $\{A_i, B_i\}$ due to resource constraints in electronic controls and synchronisations. Note that all 10 wavelength channels maintained parallel fibre transmission connecting the 20 client-chips during sequential QKD operations, with non-target channels at high intensity to estimate an upper bound for crosstalk and noise (emulating realistic scenarios). Our implementation combines established dual- λ phase tracking and postselection^{20,48,49} maintaining system simplicity while ensuring sufficient stability, with microcomb-enabled coherent WDM, which together provide an efficient solution for QKD network. Details are provided in Supplementary Information 4.

2. In general, the description of the implementation of dual-lambda method is poor. They refer to paragraph 3.2 of the supplementary materials which is extremely synthetic. I suggest they better explain how they perform this operation in particular highlighting, for example, how the frequency and phase noise on the channel can be influenced by the noise of the microcomb or how the fluctuation of the residual phase noise could affect the QBER. As the referee suggested in comments 1 and 2, we have added a sentence in the main text Page 4: "The dual- λ phase tracking was implemented via 5 ms windows to measure quantum-reference phase difference Φ_d , enabling continuous operation through 15 ms key distribution."

We have significantly revised Supplementary Section 4.3 to explain the dual-lambda and postselection method:

4.3 Global phase tracking with dual- λ method

The raw key obtained from the interference at the server node hinges on ensuring that it receives the signals as anticipated by users, notwithstanding the various signal degradations over long fibres. The primary factor influencing the interference result is the fluctuation of the relative global phases between Alice and Bob, which can be ascribed to phase noise from lasers and accumulated phase shifts in the fibres:

$$\Delta = \phi_A - \phi_B = \Delta_{\text{laser}} + \Delta_{\text{channel}}. \quad (\text{S23})$$

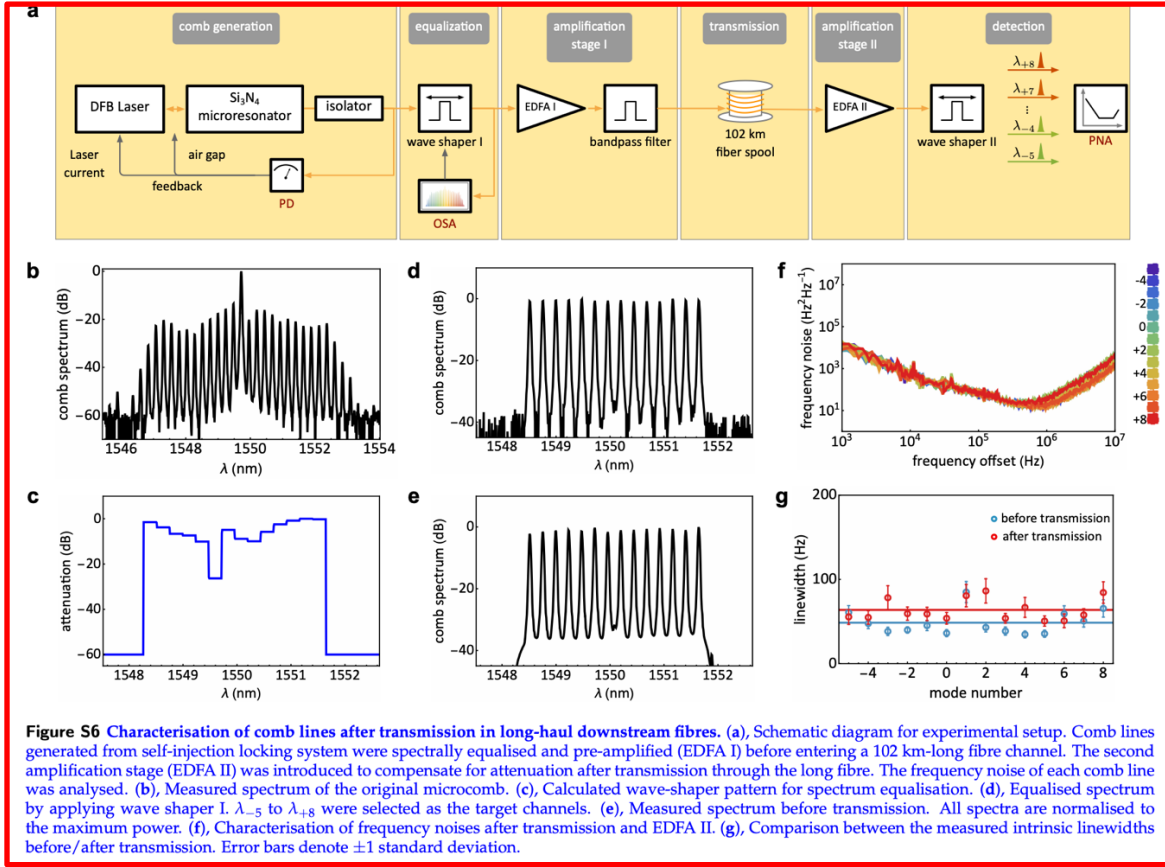
In this work, the upstream and downstream channels form a large-scale closed MZI for the signal transmission. The adoption of ultra-low-noise lasers by injection locking local DBR lasers to microcomb lines, the laser phase noise Δ_{laser} can be significantly reduced. We adopted the dual- λ method to track and estimate phase shifts in channels Δ_{channel} by comparing co-propagating wavelengths, retrieving only residual slow fluctuations undergoing the same fibre. The dual- λ method also helps diminish the noise stemming from double-Rayleigh scattering in the time-multiplexing scheme and enhances the signal duty cycle^{18,75}.

The system tracks global phases between users but without performing active compensation. These global phases act on the user-encoded optical fields and ultimately determine the long-distance single-photon interference visibility (see Eq. S16). The ultimate phase interval selection in the X-basis depends on the combined effects of $\{\delta_A, \delta_B, \phi_A, \phi_B\}$. Because the values of randomly chosen $\{\delta_A, \delta_B\}$ are announced publicly for verification, the difference between (i), real-time compensation of the global phases or (ii), real-time tracking with postselection (which is the case in this work) is whether $\phi_B - \phi_A$ could be regarded as a constant preset value $\Delta(t) = \Delta(0)$ or time-varied known value $\Delta(t)$. Both approaches ensure uniform phase distribution in $[0, 2\pi)$ of the total relative phases, because the global phases Δ follow the uniform temporal distribution. Therefore, both phase compensation and postselection methods yield identical proportions of effective events satisfying Eq. S16, with no additional event loss. Both global phase compensation^{18,19,21} and postselection^{20,48,49} have been widely implemented in TF-QKD experiments. Phase postselection can simplify the system by eliminating feedback loops. In this work, we intentionally adopted phase postselection to streamline system complexity, focusing on demonstrating scalable integrated photonic hardware for TF-QKD networks. That being said, regarding key rate performance, there is no fundamental difference between using post-selection or phase compensation since phase randomisation (required for decoy-state protocols) inherently involves post-selection in X_{11} -basis. However, for field-deployed QKD systems, phase compensation offers a practical advantage by eliminating the additional data sifting step required in post-selection approaches. In such implementations, phase compensation methods can be independently applied in fibre channels.

In our network configuration in Fig.1a, users within the same metropolitan zone share common upstream/downstream backbone fibres (spanning hundreds of kilometres) connecting the server and intermediate nodes, while requiring dedicated short-reach fibres between client nodes and the intermediate node, resulting in each client-server connection comprising both shared long-haul and short fibre segments. When these dedicated fibres are sufficiently short with slow phase drift rates, metropolitan users can share a common reference wavelength (because of the locked phases between all comb lines generated by the same high-stability microcomb) for phase tracking instead of requiring individual reference wavelengths. Our phase postselection implementation announces all reference wavelength phase shifts, enabling neighbouring users to select appropriate phase windows for data sifting. When the dedicated fibres' length becomes excessive, the phase drifts accelerate, necessitating separate reference and quantum wavelengths for each user. For our experimental demonstration under stable laboratory conditions, we employed a common reference wavelength λ_0 with sequential phase tracking for user pairs while maintaining all other quantum signal transmissions (without detection). The statistical characteristics of phase shifts in the fibre spools demonstrated temporal stationarity (see results in Fig.3), validating this method for evaluating simultaneous phase tracking across all channels.

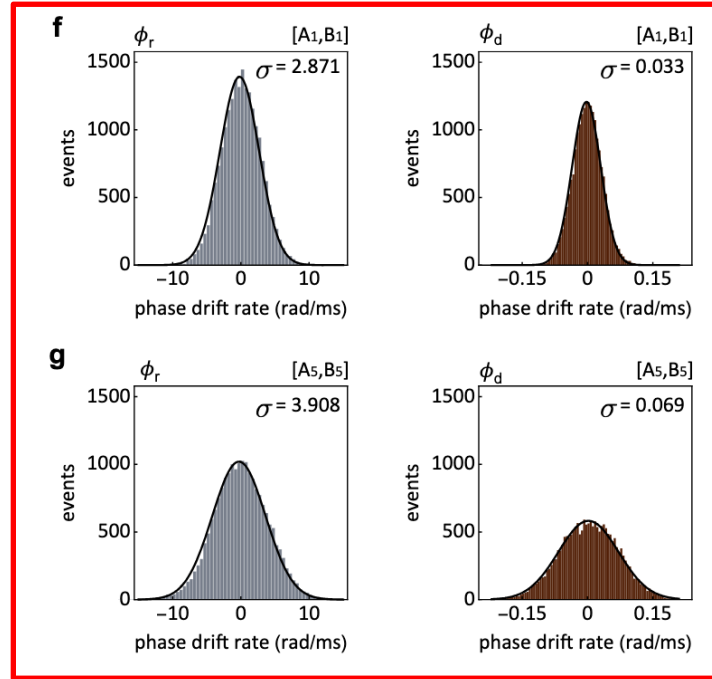
We clarify and summarise several characteristics of the entire phase-locking system, from the server chip's self-injection locking microcomb to user chips' injection-locking lasers, and phase tracking in the fibre channels. 1), The self-injection locking microcombs exhibit exceptional stability and superior performance. 2), The local slave lasers, phase-locked with the microcombs through injection-locking, also show high resilience to perturbations commonly encountered in standard monolithic devices, such as those induced by back-scattering to the DBR lasers. In addition, fluctuations in seed light intensity can be effectively re-stabilised at the user chips³⁰, with minimal impact on laser output intensity. Phase-locking of server's microcomb lasers and clients' slave lasers refers to the suppression of phase noises, which are characterised by frequency noises spectra and linewidths, as reported in Fig. 2 of the main text. 3), In quantum channels connecting the server node and client nodes, our streamlined approach that combines dual- λ methods and microcomb-enabled coherent WDM techniques (see the above paragraph), simplifies phase tracking and locking by obviating the need for intricate electronic controls, redundant ultra-stable cavities, and complicated phase controls in the channels. The microcomb-driven integrated photonic devices enable reliable transmission across WDM quantum channels, thereby providing an efficient solution for multi-wavelength, multi-user and long-haul TF-QKD networks.

We thank the referee for pointing out the necessary to discuss how the frequency and phase noise on the channel can be influenced by the noise of the microcomb and how the fluctuation of the residual phase noise could affect the QBER. First of all, following the referee's suggestion, **we implemented a new characterisation of the frequency noise on the channel when the comb lines are transmitted through long fibre channels** (here, we adopted a 102 km-long fibre). **New results are shown in Fig.S6. These results show near the same linewidth before/after transmission through the channel for all 13 wavelength channels (Fig.S6g).** We have added a new Supplementary Section 5.1 "Network with symmetric upstream-downstream channels".



The total phase noises can be distinguished into the parts from lasers and fibres, that is $\Delta = \phi_A - \phi_B = \Delta_{\text{laser}} + \Delta_{\text{channel}}$ (see Eq. S23). That means, laser frequency noises eventually contribute to the total phase noises. As we have highlighted in the **Supplementary Section 4.3**, the adoption of ultra-low-noise lasers by injection locking local DBR lasers to microcomb lines, the laser phase noise Δ_{laser} can be significantly reduced. In any case, the QBER in the X-basis of our system depends heavily on the interference outcomes, where residual phase noise plays a critical role. Within the SNS-TF-QKD protocol, the phase-flip error rate is estimated through the QBER measured in the X-basis (see Eq. S20). The SNS-TF-QKD protocol provides reliable QBER estimation even under these conditions, as originally demonstrated in the foundational proposal (Phys. Rev. A 98, 062323 (2018)). The protocol's robustness stems from its inherent design that decouples phase-sensitive single-photon interference from secure key generation, while tolerating larger misalignment error than the original TF-QKD protocol. In our current implementation, we achieve high phase stability, resulting in maintained QBER_X values of 2.87-4.17% across all 20 client chips.

As the referee suggested, to characterise how residual phase noise affects QBER, **we have also reimplemented dual- λ phase tracking and TF QKD with long downstream fibres, when more phase noises may be introduced.** In this new experiment, we fully characterised phase tracking of two InP transmitter chips (indicated by A5 and B5, as an example) with 120 km downstream fibres. **These new results in Fig.3g in the revised main text** show a similar phase drift rate in 120 km long fibres and short fibres, which validates phase tracking in TF QKD systems with long fibres. **In the new Fig.4**, we also measured the QBER and secured keys for the network employed short and long downstream fibres. Results in Fig.4 imply similar performances of QBER and secured keys by using the short and long fibres.



In the Fig.3 caption, we have now added: *"The fibre network employed 370 km upstream (185+185 km) and predominantly short downstream links, except for the {A5, B5} paired QKD which adopted 120 km downstream fibres. Phase information was extracted via SNSPD-based single-photon interference measurements (10 kHz sampling rate). Data were collected sequentially for each pairwise connected QKD chips at their wavelength channel, while maintaining continuous operation of all other wavelength channels multiplexed in the same fibres. (e). An example of phase distributions for the {A1, B1} paired QKD chips. Inset: zoom-in view of the initial 100 ms window. (f) and (g). Measured phase drift rate: (f) $\Phi_r = 2.871$ rad/ms and $\Phi_d = 0.033$ rad/ms for short downstream links {A1, B1}, and (g) $\Phi_r = 3.908$ rad/ms and $\Phi_d = 0.069$ rad/ms for long downstream links {A5, B5}. These results verify effective injection locking on local QKD chips and robust phase tracking in TF-QKD systems, with long-haul upstream and downstream fibres"*

In the Fig.4 caption, we have now added: *"(b) and (d), Segmented QBER in the X-basis and their statistical distributions in the 370 km upstream channels. Each data point represents the error rate measured by sending a total of 150×10^6 bins. The network employed short downstream fibres, except for the {A5, B5} with 120 km downstream fibres."*

In the revised main text page 6, we have added: *"For experimental simplicity, short downstream fibres were used in above measurement, except for the {A5, B5} user pair where 120 km (60 + 60 km) fibres were used to characterise the network with realistic long downstream fibres. We characterised injection locking and frequency noise, when combs were transmitted through long downstream fibres and consecutively reamplified (see Fig.S6), achieving comparable performance to short-haul configurations. In Figs. 3f,3g, comparative results reveal accelerated phase drift in long downstream fibres (see ϕ_d , ϕ_r for {A1, B1} and {A5, B5}). This behaviour emerges from the formation of a giant interferometer, where injection-locked lasers replicate the seed light's phase information. Despite increased drift, phase tracking can be achieved by simple adjustment of phase correction cycles as the following: Φ_d was recalibrated every 2 ms (5 ms cycle) for {A5, B5} versus every 5 ms (20 ms cycle) for other pairs."*

As the referee suggested, to comprehensively discuss the **laser's frequency noises**, in **Supplementary Section 5.2**, we have analysed a case of asymmetric QKD networks where the downstream and upstream fibre channels form a giant asymmetric MZI and the laser noise dominates **(see our response to the referee's comment 6)**.

Another critical consideration involves addressing asymmetric channel lengths between users, a key challenge in real-field application. In QKD implementations, channel length asymmetries cause differential loss for quantum states transmitted by different users, requiring protocol parameter optimisation to accommodate these variations⁸⁶. A more immediate challenge arises in experimental implementations:

asymmetric channel lengths eventually form a giant asymmetric MZI, thereby dominating laser phase noise in interference output. While adding compensating fibres to balance arm lengths can improve symmetry²², this approach becomes increasingly impractical in large-scale networks with complex topologies. A more practical approach involves developing laser sources with narrower linewidths. After injection locking at the client nodes, our laser sources exhibit narrow instantaneous linewidths of about 60 Hz. Further linewidth reduction of the microcomb can be achieved by suppressing low-frequency noise components (Fig. 2l) through co-packaging the InP DFB laser with

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Si_3N_4 microresonators to mitigate mechanical vibration effects, combined with laser locking to a stable frequency reference. An alternative approach using microresonators with larger modal volumes reduces thermo-refractive noise but compromises FSR, creating deviations from standard ITU channel spacings that require application-specific trade-offs. By synergistically combining these techniques, fully integrated lasers achieving 1 Hz linewidths become feasible⁸⁷, which show the potential to enhance tolerance to channel length disparities in TF-QKD.

3. Then, a comment by the authors on the characteristic time scales of the measurement could be useful to connect the information provided in figures 2(f-k) to those in figure 2(m).

We thank the referee for highlighting the necessary to clarify the connection between Figs. 2(f-k) and Fig.2(m) in the original manuscript. Figures 2(f-k) present the performance of self-injection-locked microcomb lasers in the server chip and optical injection-locked DBR lasers on the InP client chips, which are associated with the initialisation process shown in the flowchart in Fig. 2(m).

In the revised Supplementary Section 4.1 "Dark-pulse microcomb generation at the server chip", we have added details that indicate the characteristic time scales of self-injection-locked microcomb: "Under the condition of small detuning between the laser and microresonator's mode, we implemented 1 kHz sawtooth-wave current scanning of the DFB laser while performing synchronous coupling air gap adjustments to identify the optimal dark-pulse frequency comb generation regime. This procedure enabled determination of the optimised laser current and coupling air gap parameters, allowing subsequent turnkey acquisition of the microcomb outputs through direct loading of predetermined current values to the DFB laser under invariant experimental conditions."

In the revised Supplementary Section 4.1 "Quantum keys encoding at the InP client chips", we have now added details that indicate the characteristic time scales of optical injection-locked DBR lasers: "The detuning range was initially determined by synchronously adjusting above operating parameters to make robust injection-locking operation. Subsequently, with all parameters (including seed light power) maintained constant, stable locking states can be reliably achieved during each experimental run through rapid SOA current scanning until reaching predetermined values. Such procedures allow for individual calibration for the lasers across all 20 client chips."

In addition, we have significantly revised the layout of Fig.2 and Fig.3 to improve clarity. In the new Fig. 2, we have now included extensive experimental data characterising 20 InP transmitter chips, verifying their yield, reproducibility, and scalability (see our response to the referee's Comment 5). In the new Fig.3 and Fig.4, we have now incorporated recollected data for dual- λ phase tracking (see our response to the referee's Comments 1,2) and the TF-QKD network with 20 client chips. Given these updates, the system-level operation flowchart is more appropriately placed in Fig.3 for better readability. The flowchart has been relocated to Fig.3a.

4. TF-QKD is a protocol useful for long distance QKD. Why the authors decided to use an optical link of 102 km + 102 km, where Twin-Field QKD doesn't overcome the PLOB bound?

The referee is absolutely correct that our 102 km + 102 km implementation does not surpass the PLOB bound. In our new experimental demonstration of the TF-QKD network using 20 independent InP transmitter chips, we deliberately tested two configurations:

A 102 km + 102 km implementation that does not exceed the PLOB bound (results in Figs. 4a, 4c, and 4e).

A 185 km + 185 km implementation that does surpass the PLOB bound (results in Figs. 4b, 4d, and 4f).

The first configuration was used to verify that our chip-based TF-QKD network follows the expected theoretical key rate-distance relationship (as clearly evidenced in Extended Data Fig. 1), while the second configuration demonstrates successful overcoming of the PLOB bound.

We have clarified this distinction in both the revised main text and the caption of Extended Data Fig. 1.

In the main text Page 7, we have added: *"As anticipated, in Fig.4e, the key rates does not exceed the PLOB-repeaterless bound at 204 km distance, but aligned well with the expected theoretical rate-distance relationship in Extended Data Fig.1"*.

In the caption of Extended Data Fig. 1, we have now added: *"Two configurations were implemented in experiment: case 1): 204 km upstream fibres that does not exceed the PLOB bound, and case 2: 370 km upstream fibers that does surpass the PLOB bound. The 204 km configuration was used to verify that our chip-based TF-QKD network follows the expected theoretical key rate-distance relationship. At the distance of 370 km, all TF-QKD across 20 client-chips successfully exceed the PLOB-repeaterless bound."*.

5. The text provides extensive details on microcombs but lacks sufficient information on the single-photon aspects, such as the specifications of the single-photon detectors and the residual background photons resulting from the dual-band technique. In the discussion section, the authors suggest that using SNSPDs can enhance the performance of their approach. However, if I understand correctly, SNSPDs were already used in this experiment. Overall, the authors should improve the clarity and effectiveness of their description of key technical aspects, ensuring a better understanding of the reliability and advantages of the Twin-Field transmission.

We appreciate the referee's comment, noting that the previous manuscript version emphasised microcombs but required further elaboration on the single-photon aspects. We agree with the referee that **single-photon aspects** including single-photon detection at the server node (including background noise in channels) and single-photon-level operation on the InP chips are important in our demonstration. In particular, we fully agree with the referee that characterising **InP QKD chips, including their single-photon-level operations** is really important, as it can tell whether InP QKD client chips can provide high scalability through the fabrication and operation of multiple nearly identical chips (also pointed out by the referee 1 and referee 3). We have now recollected all data for 20 InP client chips including single-photon data in Fig.2, Fig.3 and Fig.4. We have

emphasized a critical advancement: the scalability of InP QKD chips, which we have now demonstrated in the revised manuscript. To balance the microcombs and single-photon aspects, we have significantly modified Fig.2 and relocated some microcombs data to Supplementary Information and included more InP client chips data. To ensure experimental results are presented with roughly equal rigour, and following the Editor's suggestion to streamline the title, we have revised it to: "Large-scale Quantum Communication Networks with Integrated Photonics" (replacing the title for the initial submitted version: "Scaling Quantum Communication Networks with Microcomb-Driven Integrated Photonics").

5.1 Single-photon detection at the server of TF-QKD network using SNSPDs.

First of all, the referee is correct that SNSPDs have been used in our current experiments. The discussion of "incorporating low-noise SNSPDs, it becomes feasible to extend the reach of individual communication links to a thousand kilometres." in the original manuscript indeed causes some potential misleading. By using "low-noise" actually refers to the SNSPDs with tens of mHz dark count rate as used in the 1000 km TF-QKD experiment [Phys. Rev. Lett. 130, 210801 (2023)]. Now, we have improved the statement in the revised manuscript Page 7: "Note that the communication distance is primarily limited by the dark counts of SNSPDs." and "Through incorporating SNSPDs with lower dark count rate, it becomes feasible to extend individual quantum communication links to 1000 km distances20."

We thank the referee very much for insightfully pointing out the potential residual noise photons from the dual-band technique. Especially, when all wavelength-multiplexed channels are parallelly running in the same fibre, it is possible that nonlinear optical effects such as spontaneous Raman scattering (SRS) may pose additional noise photons. In the revised manuscript, we have implemented pairwise QKD between 20 InP chips through one wavelength channel, while maintaining parallel transmission of all other quantum signals in the same fibre. **This configuration have set the worst case of crosstalk and noise photons that may increase QBER. Our results showed that the SRS noise contributed to be less than 1.7 counts per second, which is negligible compared to SNSPDs' dark count rate. As the referee suggested, these results and analysis have been provided in a new Supplementary Section 4.4 and Table S4.**

	λ_{-5}	λ_{-4}	λ_{-3}	λ_{-2}	λ_{-1}	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5
counts of D_{qL} (ref. off)	19.14 $\pm$ 3.98	19.39 $\pm$ 5.65	18.57 $\pm$ 5.15	16.90 $\pm$ 2.51	13.03 $\pm$ 3.64	15.19 $\pm$ 4.78	11.54 $\pm$ 2.20	13.61 $\pm$ 3.35	11.61 $\pm$ 3.69	16.60 $\pm$ 2.98	
counts of D_{qR} (ref. off)	20.92 $\pm$ 3.76	18.26 $\pm$ 4.21	15.76 $\pm$ 4.25	17.48 $\pm$ 6.30	15.44 $\pm$ 3.33	21.96 $\pm$ 3.06	12.96 $\pm$ 3.83	14.36 $\pm$ 4.75	13.35 $\pm$ 3.46	15.15 $\pm$ 4.15	
counts of D_{qL} (ref. on)	19.90 $\pm$ 2.67	20.51 $\pm$ 3.21	16.05 $\pm$ 4.44	17.13 $\pm$ 6.97	11.65 $\pm$ 3.20	14.82 $\pm$ 5.50	10.90 $\pm$ 3.84	13.98 $\pm$ 3.61	12.20 $\pm$ 3.21	16.77 $\pm$ 5.43	
counts of D_{qR} (ref. on)	20.95 $\pm$ 3.57	17.82 $\pm$ 3.67	15.89 $\pm$ 6.03	24.44 $\pm$ 6.97	14.74 $\pm$ 3.29	25.20 $\pm$ 4.31	11.00 $\pm$ 1.91	15.00 $\pm$ 3.89	12.12 $\pm$ 4.09	15.77 $\pm$ 3.98	

Table S4 Dark count and noise measurements in different configurations. The reference on/off condition refers to the activation/deactivation of both the λ_0 reference signal and all non-target wavelength channels λ_i (set to the maximum intensity required for phase tracking). To measure the baseline detector noise, the target wavelength channel was disabled during these measurements. This characterisation confirms negligible SRS noises compared to SNSPDs' dark count rate. The dark count rates represent 1-second averages, with error bars indicating the standard deviation across 10 consecutive measurements. Counts for D_{qL} and D_{qR} are shown by cps.

4.4 Noises in fibre channels

In the experiment, where both reference and quantum signals coexist, the issue of additional noise photons must be taken into consideration. Compared to phase tracking using time-multiplexing methods^{18,75}, the noise photons from the double-Rayleigh scattering process in this study are reduced by using the wavelength-multiplexing dual- λ method. The reference signal does not affect the quantum signal through this process since they are at different wavelengths. The impact of scattered photons from the bright quantum signal (used for recalibrating the phase difference reference Φ_d) is minimised due to its shorter time occupancy.

It is necessary to consider nonlinear noises when nonlinear optical effects pose non-negligible constraints in the WDM architecture. In the experiment, reference signals are also detected by single-photon detectors, and all wavelength-channel signals in the upstream fibres are maintained at the single-photon level. The dominant noise photons arise from spontaneous Raman scattering (SRS), while four-wave mixing remains negligible due to the low optical intensities employed. Photons have a chance of being inelastically scattered to shorter (anti-Stokes) or longer (Stokes) wavelengths. The intensity of SRS noise photons is directly proportional to the power of the pump light and the bandwidth of the spectral filter. We consider a fibre channel of length L_f , where N_{total} optical signals are propagating in the same direction, each with intensity of P_i at wavelength λ_i ($i = 1, 2, \dots, N_{\text{total}}$). Then the intensity of SRS photons received at wavelength λ_k ($k = 1, 2, \dots, N_{\text{total}}$) with an optical bandwidth $\Delta\lambda_k$ can be calculated as

$$P_{k,\text{SRS}} = \sum_{i \neq k} P_{i,\text{out}} \cdot L_f \cdot \rho_{ki} \cdot \Delta\lambda_k, \quad (\text{S24})$$

where ρ_{ki} denotes the effective SRS cross section for scattered photons from λ_i to λ_k , $P_{i,\text{out}}$ denotes the intensity of λ_i photons at the fibre output. We use the maximum SRS cross section⁷⁶ over telecommunications-C band $\rho_{\text{max}} = 6 \times 10^{-9} (\text{km} \cdot \text{nm})^{-1}$ to substitute for any possible combination of $\rho_{i,k}$ ($i, k = 1, 2, \dots, N_{\text{total}}$).

As discussed in the main text, we implement a worst-case scenario where all non-target wavelength channels operate continuously at maximum intensity $n_{\text{max}} = 2\text{M}$ counts per second (cps) during phase estimation, while a single targeted wavelength channel performs QKD. This will result in the maximum output intensity $P_{\text{max}} = n_{\text{max}}hc/\lambda$, where hc/λ is the single photon energy. Wavelength selection at the server node is accomplished with the fibre Bragg grating filters with bandwidth $\Delta\lambda = 0.08 \text{ nm}$. Under these conditions, the remaining SRS

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noise photons in channel k satisfy:

$$\frac{hc}{\lambda_k} n_{k,\text{SRS}} < (N_{\text{total}} - 1) \cdot \frac{hc}{\lambda_{\text{min}}} n_{\text{max}} \cdot L_f \cdot \rho_{\text{max}} \cdot \Delta\lambda, \quad (\text{S25})$$

where $n_{k,\text{SRS}}$ denotes the noise photon count rate induced by SRS from all other wavelength channels. For our implemented system with $L_f = 185 \text{ km}$ and $N_{\text{total}} = 11$, we estimate the SRS noise contribution to be $n_{k,\text{SRS}} < 1.7 \text{ cps}$, which is negligible compared to the SNSPDs' dark count rate. This conclusion is further supported by the crosstalk characterisation data presented in Table S4, which shows minimal variation in dark count rates when comparing measurements with all parallel wavelength channels activated versus deactivated.

As the referee suggested, to ensure a better understanding of the advantages of TF-QKD, a type of MDI-QKD, we have added a sentence to highlight its resource-sharing capability in the main text Page 7: *"For example, at the server side, integrating devices such as SNSPDs, frequency shifters, and linear optic circuits^{14,59,60} alongside microcombs could enhance scalability, connectivity, and cost-effectiveness of entire networks."*

We have also added a new Supplementary Section 5.2 to discuss single-photon frequency conversion that can improve the connectivity of the network between users with different quantum signal wavelengths. (please see our response to the referee's comment 8).

In the Supplementary Information Section 4, we have added details of quantum keys encoding at the InP client chips, WDMed Quantum channels in fibres, and single-photon detection at the server node.

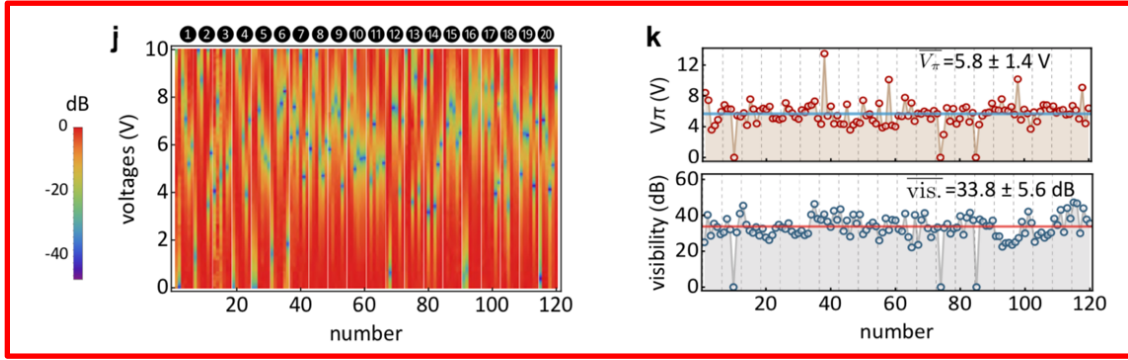
Quantum keys encoding at the InP client chips: Laser diode controllers were used to control the SOA section of on-chip DBR lasers and the chip's temperature, and the DBRs were controlled with additional voltage sources. The frequency detuning with the microcomb seed light could be carefully controlled to achieve injection locking conditions. The detuning range was initially determined by synchronously adjusting above operating parameters to make robust injection-locking operation. Subsequently, with all parameters (including seed light power) maintained constant, stable locking states can be reliably achieved during each experimental run through rapid SOA current scanning until reaching predetermined values. Such procedures allow for individual calibration of the lasers across all 20 client chips. The DBR lasers were running in continuous mode. For pulsation, electrical signals from high-speed arbitrary waveform generators (AWGs) were amplified and mixed with DC bias signals, and then fed into the IMs III. Additional AWGs were used to generate the electrical control signals for the PM I and IM I, II according to the sequence shown in Fig. 3a to finish the phase randomisation and coding, and decoy state preparation and attenuation. Experimental characterisations of optical injection locking of local DBR lasers and modulators are provided in Fig. 2 of the main text. Figures 2j and 2k demonstrate the high yield of our electro-optic modulators, with 97.5% (117 of 120) functioning as designed under normal operating conditions, while 3 devices exhibited failures due to fabrication imperfections. The device's design allows for flexible configuration. We successfully implemented a single-drive scheme using one electro-optic PM (EOPM) per IM as an alternative to the dual-drive push-pull configuration (which would require two EOPMs per IM). This adaptability ensured full operational capability across all 20 independent InP chips in the QKD network.

WDMed Quantum channels in fibres: The reference and quantum signals were wavelength-multiplexed and transmitted in the long-haul upstream fibre spool back to the server node simultaneously. The upstream channel distance from Alices' and Bobs' node to the central server node and corresponding fibre losses are provided in Table S3. Constrained by limited RF resources, we simulated concurrent multi-user communication by implementing the whole quantum state encoding procedure in sequence for the selected user pair while leaving other non-target wavelength signals unmodulated and directly injecting into the upstream fibre channels. To evaluate worst-case crosstalk, these non-target wavelength signals were maintained at maximum intensity levels required for phase tracking (see Section 4.3). To simplify the system for a proof-of-principle demonstration of TF-QKD network, the downstream fibres from the microcomb to the QKD client-chips were replaced by short fibres in most cases, except for the user pair $\{A_5, B_5\}$, where 120 km-length (60+60 km) downstream fibres were used. We confirm comparable phase drift and phase tracking for short and long downstream fibres in Fig.3 and implement TF-QKD in both cases in Fig.4. Detailed performance characterisation regarding the introduction of long downstream fibres is presented in the main text and further discussed in Section 5.1.

Single-photon detection at the server node: The demultiplexed signals were routed into pairs to implement the dual- λ phase tracking. Fibre Bragg grating filters (with a 0.08 nm bandwidth) were used to segregate the reference and quantum signals, exhibiting low insertion loss (about 1 dB each), and single-stage filtering depth of 30 dB (cascading two Bragg filters will achieve 60 dB), see Tab. S3. To simplify the client chips, the phase modulator for the reference signal was placed at the server node to perform the four-phase estimation method. All optical signals after interference were detected by superconducting nano-wire single-photon detectors (SNSPDs) and recorded with a high-precision multi-channel counting module. The recorded signals were used for subsequent data post-processing. Throughout the network, the clocks of all dynamic control and detection components were precisely synchronised using electrical signals. In addition, optical frequency comb has been commonly used in both classical and quantum communication networks²², and thus integrated microcomb could be used for clock synchronisation in the QKD network. In future, it is possible to leverage dark-pulse microcomb for integrated optical synchronisation, since these microcomb exhibit exceptional coherence and can simultaneously serve as optical synchronisers and RF synthesizers⁷³. This approach would enable fully optical synchronisation while maintaining the TF QKD system's functionality.

5.2 Single-photon operation using 20 separated InP QKD chips

In addition, inspired by the referee's comment on insufficient information on the single-photon aspects, **we have packaged and characterised 20 copies of InP QKD client-chips to verify their yield, reproducibility, and scalability, and system-level operation of the TF QKD network consisting of 20 client chips.** For QKD based on weak coherent states, key parameters of modulators are the $V\pi$ of phase modulators and modulation visibility of intensity modulators, as these parameters fundamentally determine the driving efficiency and QBER of the QKD system. **We have now implemented full characterisations of 120 independent PMs and IMs on 20 separated InP chips, and results are reported in new Fig.2j, Fig.2k and Fig.2i.** We therefore demonstrate high yield modulators with a $V\pi$ of 5.8 ± 1.4 V and a high modulation visibility of 33.8 ± 5.6 dB. All EO modulators functioned as designed under normal operation, while 3 out of 120 modulators showed failures due to fabrication imperfections, yielding a high yield rate of 97.5%. Fortunately, we could implement a single-drive configuration using one of the EOPMs in each IM, instead of a push-pull dual-drive configuration using two EOPMs in each IM, ensuring fully operational QKD networks using 20 independent InP chips. We have added this detail in **Supplementary information Section 4 "Quantum keys encoding at the InP client chips".**



In the revised main text Page 4, we have added a paragraph to describe the details of InP chip characterisations.

The phase modulation was achieved using a single-arm electro-optic PM (EOPM), while intensity modulation was implemented using Mach-Zehnder modulators (MZMs) with dual-arm PMs (with 1.25 mm length, 25 GHz bandwidth) for loss balance and high extinction ratio. Figure 2j reports the measured modulation curves for all EOPMs in IMs. It shows 117 of 120 EOPMs (i.e. 97.5% yield) functioning as designed across all 20 chips, with three hardware failures. These modulators exhibited consistent performance, as shown in Fig. 2k, with an average V_{π} of 5.8 ± 1.4 V and interference visibility of 33.8 ± 5.6 dB.

6. To improve the article, the authors could give some additional details regarding the metrological characterization of the microcomb. In fact some information can be intuited from the caption of figure 2, but in the article they are barely mentioned. So I suggest to address the metrological part by adding this information in the supplementary materials. In particular, I suggest to better explain in the text what the authors mean by synchronization and stabilization.

We sincerely appreciate the referee's valuable suggestions regarding the characterisation of microcombs and experimental implementation details. As the referee suggested, we have now relocated some of the microcomb characterisation data to Supplementary Information. For example, the measured spectral response of the SiN high-Q microresonator (previously Fig. 2d in the original manuscript) is now presented in Fig. S1; The microcomb beatnote spectrum (previously Fig. 2k in the original manuscript) is now presented in Fig. S7c. In the revised Supplementary Section 1 and Supplementary Section 4.1 "Dark-pulse microcomb generation at the server chip", we have now provided metrological characterisation of the microcomb.

We thank the referee for the comment on the terminology of synchronisation and stabilisation.

"Synchronisation" refers to the clock synchronisation between QKD users in the quantum network. In the revised manuscript, we have removed all terminology of synchronisation to describe phase-locking behaviour in the microcomb and local DBR lasers to avoid misleading.

"Stabilisation" refers to the stabilisation of the self-injection-locked microcomb laser. In the revised manuscript, we have removed all terminology of stabilisation to describe phase behaviour in channels to avoid misleading.

"Synchronisation": In our current experiment, we employed RF-based synchronisation via electrical signals to minimise system complexity, as shown in Fig. S3. Optical synchronisation is critical for real-world deployment.

Recent advances demonstrate successful optical clock synchronisation in quantum networks [Nature 640, 911–917 (2025)]. In future, it is possible to leverage dark-pulse microcomb for integrated optical synchronisation, since these microcombs exhibit exceptional coherence and can simultaneously serve as optical synchronisers and RF synthesisers [see our recent work in Nat. Electron. 8, 322–330 (2025)]. This approach would enable fully optical synchronisation while maintaining the TF system's functionality. In the current demonstration, we prioritised simplicity in the QKD implementation by RF synchronisation in the laboratory.

In the revised main text Page 6, we have added a sentence: *"Device clocks were currently synchronised via electrical signals (see Fig.S3), while in future microcomb could enable practical clock synchronisations."*

In the revised main text Page 6, we have now added a sentence: *"Phase tracking and key distribution were sequentially executed between paired chips {Ai, Bi} due to resource constraints in electronic controls and synchronisations."*

We have added a detailed discussion of optical synchronisation prospects in Supplementary Section 4.1 "Single-photon detection at the server node".

of all dynamic control and detection components were precisely synchronised using electrical signals. In addition, optical frequency comb has been commonly used in both classical and quantum communication networks²², and thus integrated microcomb could be used for clock synchronisation in the QKD network. In future, it is possible to leverage dark-pulse microcomb for integrated optical synchronisation, since these microcomb exhibit exceptional coherence and can simultaneously serve as optical synchronisers and RF synthesizers⁷³. This approach would enable fully optical synchronisation while maintaining the TF QKD system's functionality.

"Stabilisation": Both SiN and DFB pump chips used in the self-injection-locking dark pulse generation, were temperature stabilised using temperature controller with a 1 mK precision and 4 mK stability. We captured the comb spectrum every minute over 12 hours using an optical spectrum analyser (MS9740A, Anritsu), and the results are shown in Fig.2e. This result indicates negligible drift of the comb lines. In the revised manuscript, we have now added the relative intensity fluctuation plot in a new Fig.2f to provide a clearer characterisation of the stability. A mean value of 0.994 ± 0.006 in 12 hours denoted that the microcomb retained the steady state, highlighting the stability of the system. The microcomb was monitored with the output power and the feedback signal was used to control the DFB's current and the air gap between the laser chip and SiN chip, which has been provided in Fig.S3. In the revised Supplementary Section 4.1 "Dark-pulse microcomb generation at the server chip", we have now added more stabilisation details of self-injection-locked microcomb laser.

However, we would like to point out that our current microcomb lasers exhibit non-negligible low-frequency noise, which requires higher-level stabilisation of the microcomb device. Our current microcomb lasers pose challenges for directly implementing asymmetric TF-QKDs which challenges phase tracking in asymmetric channels between Alice-Charlie and Bob-Charlie. Such asymmetries of channels can occur in practical TF-QKD systems and may degrade performance due to finite frequency and phase stability. Successful phase tracking in such highly asymmetric configurations requires lasers with ultra-low phase noise. In the new Supplementary Section 5.2 of the revised manuscript, we have identified several promising solutions to achieve ultra-low phase noise. Optimising our system using state-of-the-art techniques, such as fully packaged self-injection-locked microcombs or fully integrated microcombs, could achieve Hz-level linewidths. Very recently, it shows that integrating photonic chips with microfabricated reference cavities could enable mHz-linewidth lasers [Nat. Photon. (2025), DOI:10.1038/s41566-025-01701-5].

7. In Fig. 2 “(g), Characterisation of spectral stability of microcombs, collected every minute over 12 hours.” I suggest explicating in which way they perform this measure. This is important to understand also the statement related to fig.2 (h) and (i) “(h), microcomb seeding lasers at the server, and (i), synchronised slave lasers on the QKD client chips”. Unfortunately, much of the information needed for a better understanding of the work is written in a rather cryptic manner in the text.

We gratefully acknowledge the referee's comments on microcomb stability characterisation and manuscript clarity. As the referee suggested, we have implemented the following improvements. The 12-hour spectrum (now Fig.2e in the revised manuscript) was captured every minute over 12 hours with an optical spectrum analyser (MS9740A, Anritsu), and we have introduced a new quantitative stability metric (we have now added a new Fig.2f to provide a clearer characterisation of the stability), demonstrating excellent intensity stability (0.994 ± 0.006) over the 12-hour measurement period.

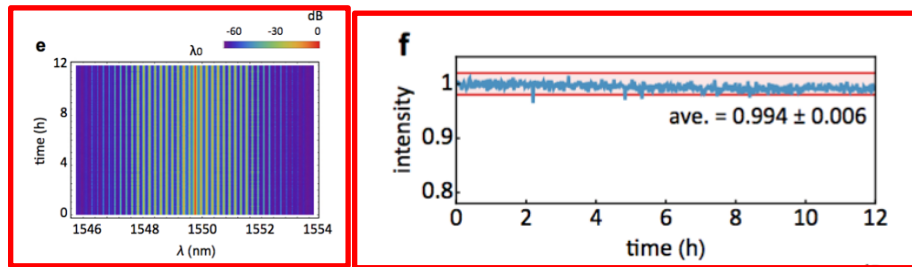


Figure 2... (e) and (f). Spectral stability characterisation of microcomb. The microcomb's spectrum was collected every minute with an optical spectrum analyser over consecutive 12 hours. The normalised intensity fluctuation (f) extracted from (e) shows excellent system stability maintaining a mean relative intensity of 0.994 ± 0.006 .

We have added a detailed description of the stability measurement in Supplementary Section 4.1:

Dark-pulse microcomb generation at the server chip: The Si_3N_4 microresonator and integrated distributed feedback (DFB) laser were mounted on the thermoelectric coolers, respectively with 1 mK temperature control accuracy. The DFB laser chip was controlled by a six-axis stage to precisely adjust the coupling angle and air gap between chips. Under the condition of small detuning between the laser and

microresonator's mode, we implemented 1 kHz sawtooth-wave current scanning of the DFB laser while performing synchronous coupling air gap adjustments to identify the optimal dark-pulse frequency comb generation regime. This procedure enabled the determination of the optimised laser current and coupling air gap parameters, allowing subsequent turnkey acquisition of the microcomb outputs through direct loading of predetermined current values to the DFB laser under invariant experimental conditions. An optical isolator was inserted at the output of the microcomb to prevent reflected noise light from disturbing the locking condition. Then, part of the microcomb was fed into the photodiode, optical spectrum analyser and phase noise analyser for monitoring and performance characterisation. The desired comb lines ranging from λ_{-5} to λ_{-3} and λ_{+2} to λ_{+8} were selected and intensity equalized with a waveshaper. An Erbium-doped fibre amplifier was used to ensure that the comb had an intensity of at least -20 dBm on-chip power when injected as seed lights onto the QKD transmitter chips. The spacing between different wavelength channels was 30.03 GHz (equal to the FSR of the microresonator), misaligning with the standard ITU channel spacing. Integrated microcombs matching standard ITU channel spacing (e.g., 50/100 GHz) can be readily implemented⁷², enabling full utilisation of mature WDM components for wavelength allocation and spectral filtering. This could facilitate cost-effective deployment in real-field quantum communication networks. After the comb line assignment based on network configuration, polarisation controllers were used to align the polarisation of the seed lights with the optical mode on client chips.

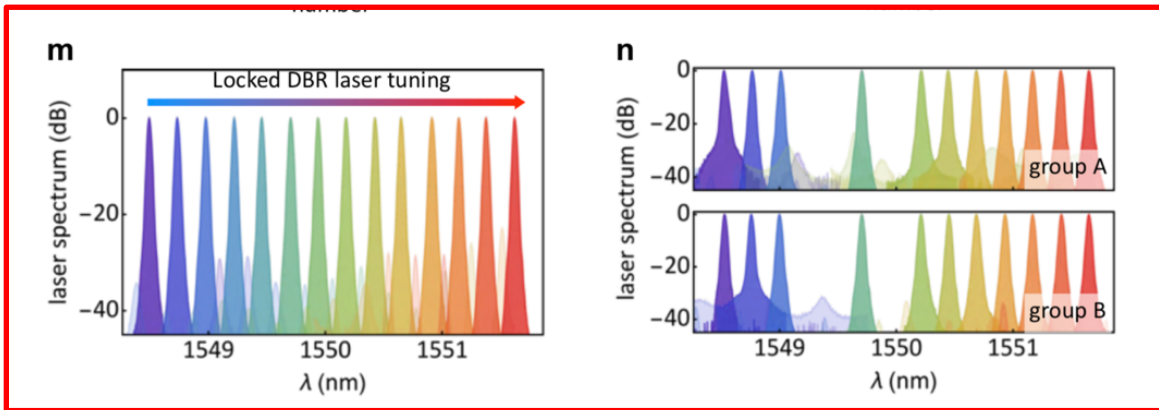
For original Figs. 2h-i (now Figs. 2g, 2l in the revised manuscript), we have added detailed the experimental procedures for power spectral density measurements of laser frequency noise by using the correlated self-heterodyne method (reference for self-heterodyne measurement is added). These methodological additions appear in the revised Figure 2 caption as: “..... (g), Frequency noise characterisation of microcomb lasers at the server. Power spectral densities were measured using correlated self-heterodyne method²⁷..... (l), Frequency noise characterisation of phase-locked slave lasers on the QKD client-chips, showing comparable performance to the microcomb (see summary in (h)). In (g) and (l), free-running lasers (black) are plotted for comparison.....”.

8. Authors declare “Microcombs with Hz-level linewidths” in fig.2 and in the text. In particular “(j), Summary of measured intrinsic linewidths for comb lines in the microcomb and synchronised slave lasers, showing narrow average linewidths of 85.6 Hz and 96.9 Hz, respectively. Points are experimental data and lines are their mean values. (k), Measured beatnote spectrum of the comb lines.” It is not clear from the text how these measures have been realized. In particular, I suggest to explicate (in the text or in the supplementary materials) the statement of fig 2(k). The beat is between the comb line and what reference..?

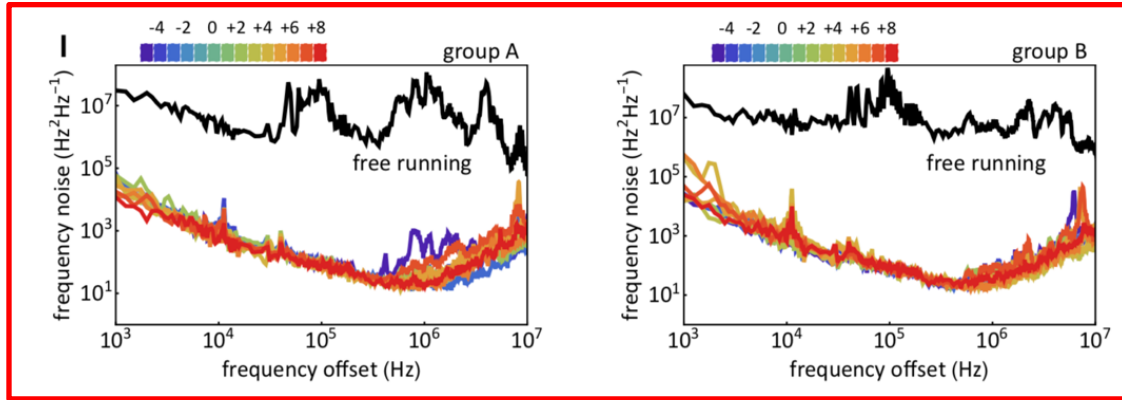
The linewidths (original Fig.2j, now Fig. 2h) were calculated from the white noise floor of the power spectral densities (original Figs. 2h,2i, now Figs. 2g, 2l), which were obtained by correlated self-heterodyne method (see our response to the referee's comment 7). We have clarified the measurement of power spectral densities and linewidths, in the revised Fig.2 caption as: “...(g), Frequency noise characterisation of microcomb lasers at the server. Power spectral densities were measured using correlated self-heterodyne method²⁷. (h), Summary of intrinsic linewidths for the microcomb and 20 phase-locked slave lasers on the client chips denoted as {Ai, Bi}. Linewidths are derived from the white noise floor of measured power spectral densities in (g) and (l).”

In addition, we demonstrated two key functionalities of the InP lasers: (i) wavelength tunability of lasers across the entire spectral range of the network, and (ii) injection-locked spectra and frequency noise, across 20 separated InP chips, with all performance satisfying the protocol requirements. We show the significant reduction of frequency noises before and after injection-locking operation across 20 separated InP chips. We also employed the wavelength tuning capability and spectral/linewidth characteristics after injection-locking operation, which directly reflect their functional reliability in actual operating conditions.

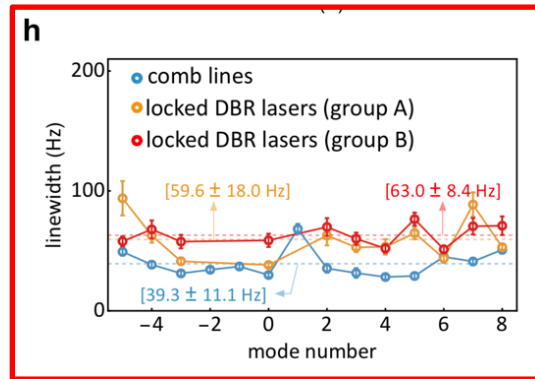
In a new Fig.2m, we have now added the measured optical spectra of a single laser continually tuning to the microcomb lines, and in a new Fig.2n, we have now added the measured optical spectra of 20 independent QKD lasers (10 lasers in group A and 10 lasers in group B in the network) on 20 separated InP chips and additional reference lasers (we show 2 lasers as examples in Fig.2n), where those lasers on separated chips have been locked to the central microcomb's lines to regenerate the quantum and reference signal.



In a new Fig.2l, we have now reported the measured laser frequency noises when they are free running and injection-locked, for those 20 independent QKD lasers (10 lasers in group A + 10 lasers in group B) on 20 separated InP chips and 2 additional reference lasers as examples.



In a new Fig.2h, we have reported the measured laser linewidth when they are injection-locked, for those 20 independent QKD lasers (10 lasers in group A + 10 lasers in group B) on 20 separated InP chips and 2 additional reference lasers. Those data for microcomb have also been reported in the new Fig.2g.



Details of comprehensive characterisations of lasers have been added in the revised main text and Fig.2 caption. Original Fig. 2(k) shows the beatnote signal has been moved to Fig.S7 in the revised manuscript. Description of the measurement method for the beatnote signal has been added in the caption of Fig. S7: “... Measured beatnote spectrum of the comb lines. The whole comb lines were separated into two arms, one of which was frequency shifted by one FSR with a 10 MHz offset before recombined. The resolution bandwidth was set to be 100 Hz.” We moved the beatnote measurement out of the main text, because this measurement indicates future possibility of implementing frequency shifting of the comb lines. An additional advantage of dark-pulse microcombs in WDM TF-QKD networks is their intrinsic phase coherence across different frequency comb lines. This property could enable reliable interference between two users operating at different wavelengths after applying single-photon frequency conversion to one user’s wavelength. Such frequency shifting is beyond our current work but it can improve the connectivity of the network between users with different quantum signal wavelengths.

We have now added a new Supplementary Section 5.2 to discuss the possibility and potential challenges.

5.2 Fully connected and asymmetric QKD networks

Future real-field implementations of multi-user long-haul quantum communication networks will require flexible configurations, including full connectivity between arbitrary pairs of QKD client chips. In WDM TF-QKD systems, quantum correlations are currently established only between users sharing identical wavelengths, as demonstrated by the black solid lines in Fig. S7a. For users operating at mismatched wavelengths, retrieving relative phase information between optical fields generally remains impossible without additional frequency conversion. To enable such connectivity, single-photon frequency shifting is demanded, requiring wavelength conversion across tens of GHz to several THz, consistent with standard ITU channel spacing in the telecommunications C-band. This can be achieved through either electro-optic (EO) or nonlinear-optic approaches, both compatible with integrated photonic platforms (see Fig. 1b). EO-based frequency shifting, implemented via high-speed phase modulation, benefits significantly from thin-film lithium niobate (TFLN) technology⁷⁸, which combines high electro-optic efficiency (> 90% shifting efficiency⁵⁷) with broad operational bandwidth (± 641 GHz⁷⁹). Nonlinear approaches leveraging $\chi^{(2)}$ or $\chi^{(3)}$ processes in periodically poled lithium niobate waveguides have demonstrated 55% single-photon conversion efficiency⁸⁰ with broadband operation across the entire C-band⁸¹, while four-wave mixing Bragg scattering in microresonator-based silicon photonic devices offers alternative implementations^{82,83}. However, current implementations face limitations including significant insertion losses and noise photon generation, restricting their immediate utility in quantum networks.

Achieving stable interference between frequency-shifted optical fields of different wavelengths fundamentally requires maintaining a stable initial phase relationship between the original fields. While multiple independent laser sources (even those with ultra-low intrinsic phase noise) would demand complex active phase-locking systems to synchronise across spectral spans potentially spanning tens of nanometres, the ultra-high coherence microcomb sources utilised in this work provide an inherent solution: all comb lines naturally preserve stable relative phase relationships throughout the entire spectral range. This critical advantage is experimentally verified in Fig. S7c, where beatnote measurements between original and frequency-shifted comb lines demonstrate equally narrow linewidths. Advanced microcomb feedback control can further enhance comb line phase stabilisation⁸⁴, implemented locally at the server node without requiring additional client-side hardware. Alternatively, heterogeneous integration techniques⁸⁵ offer complementary approaches for improving phase stability.

Another critical consideration involves addressing asymmetric channel lengths between users, a key challenge in real-field application. In QKD implementations, channel length asymmetries cause differential loss for quantum states transmitted by different users, requiring protocol parameter optimisation to accommodate these variations⁸⁶. A more immediate challenge arises in experimental implementations:

asymmetric channel lengths eventually form a giant asymmetric MZI, thereby dominating laser phase noise in interference output. While adding compensating fibres to balance arm lengths can improve symmetry²², this approach becomes increasingly impractical in large-scale networks with complex topologies. A more practical approach involves developing laser sources with narrower linewidths. After injection locking at the client nodes, our laser sources exhibit narrow instantaneous linewidths of about 60 Hz. Further linewidth reduction of the microcomb can be achieved by suppressing low-frequency noise components (Fig. 2l) through co-packaging the InP DFB laser with

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Si_3N_4 microresonators to mitigate mechanical vibration effects, combined with laser locking to a stable frequency reference. An alternative approach using microresonators with larger modal volumes reduces thermo-refractive noise but compromises FSR, creating deviations from standard ITU channel spacings that require application-specific trade-offs. By synergistically combining these techniques, fully integrated lasers achieving 1 Hz linewidths become feasible⁸⁷, which show the potential to enhance tolerance to channel length disparities in TF-QKD.

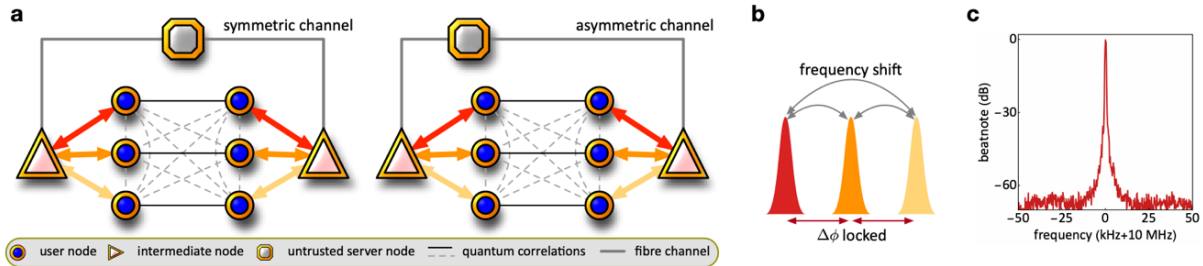


Figure S7 Extension to fully connected and asymmetric networks. (a), Schematic diagram of fully connected networks under symmetric configuration (nearly identical user-to-server channel lengths) or asymmetric configuration (substantial user-to-server length variations). Solid black lines denote pairwise quantum correlations between same-wavelength users, while dashed gray lines denote potential correlations between different-wavelength users requiring frequency conversion. (b), Single-photon frequency shifting implementation needed to enable QKD between users operating at different wavelengths. (c), Measured beatnote spectrum of the comb lines. The whole comb lines were separated into two arms, one of which was frequency shifted by one FSR with a 10 MHz offset before recombined. The resolution bandwidth was set to be 100 Hz.

9. I suggest to the authors to add a short sentence to explain the double peak of fig.2 (d)

We appreciate the referee's suggestion regarding the double peak feature in microresonator's transmission spectrum. This phenomenon naturally occurs in high-Q microresonators due to coupling between forward and backward propagating whispering-gallery modes.

In the revised manuscript, we have relocated the original Fig. 2d to Fig. S1d (Fig.2 contains too heavy data).

We have now added an explicit explanation of the double peak and improved the presentation of the microresonator transmission spectrum in Fig.S1d caption "Measured transmission spectrum for the mode 0 (refers to the mode at the wavelength λ_0), fitted with a double-peaked Lorentzian shape. The observed double-peak phenomenon naturally occurs in high-Q microresonators due to coupling between forward and backward propagating whispering-gallery modes."

We have added a sentence in Supplementary Section 2: "Measured mode splitting of the microresonator is shown in Fig. S1d (the example of mode 0) and Fig. S1e (summary of all modes)."

10. In the supplementary information, authors describe the fabrication and calibration of the microresonator. In particular, they implement a calibration of the comb spectrum by using an HCN cell. I suggest to provide more details about this operation (cell pressure, cell geometry, etc.).

As the referee suggested, we have added the description of the HCN gas cell in revised Supplementary Section 1 : "(2) a 16.5 cm fibre-coupled hydrogen cyanide (HCN) gas cell maintained at 100 Torr pressure with C-band absorption peaks serving as an absolute frequency reference (peak wavelength uncertainties on the order of 0.1 pm, see the measured absorption spectrum in Fig.S1a)", and added the measured absorption spectrum of HCN in a new Fig.S1a.

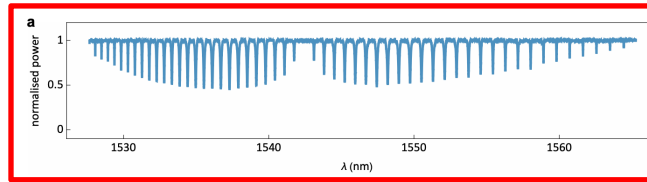


Fig.S1a: ... measured transmission spectra of the HCN gas cell...

We believe all of the referee's concerns have been thoroughly addressed both in this response letter and in the revised manuscript. We are deeply grateful for the referee's insightful and constructive comments, which have been very instrumental in helping us significantly improve our work. The thoughtful feedback has significantly strengthened both the technical rigour and clarity of our manuscript.

Referee #3 (Remarks to the Author):

In this work, the authors experimentally realized a proof-of-principle demonstration of a multi-user twin-field Quantum Key Distribution network. This network is enabled by a single optical frequency comb at the server side and multiple Indium Phosphide integrated transmitters at the user locations, all optically locked to the central frequency comb.

In particular, the authors exploit an integrated Silicon Nitride microresonator, pumped by a DFB laser, to generate highly coherent and narrow optical frequency comb lines. These comb lines exhibit approximately 90Hz short-term linewidths and span a broad spectrum of frequencies in the C-band, with approximately 30 GHz spacing between comb lines. These comb lines, generated at the central server station, are then distributed to multiple user transmitters. At each user-side transmitter, two selected comb lines are used to optically lock DBR lasers integrated on the InP PICs via optical injection locking. One comb line acts as a phase reference for the dual-lambda stabilization, while the other serves as the seed for the quantum signal. This quantum signal is then prepared and encoded on-chip for each user. The PICs include three intensity modulators and one phase modulator, used for time-bin encoding, decoy preparation, and phase randomization. In this wavelength-multiplexed configuration, each user pair utilizes a dedicated wavelength channel, resulting in $N/2$ independent pairwise TF-QKD links for N users. Finally, the encoded quantum states from each user are transmitted back to the central station via fiber spools, where they are interfered and measured using SNSPDs. The authors successfully demonstrated positive Secure Key Rates (SKR) for spooled fiber links up to 370 km, achieving key rates that surpass the PLOB bound with ten user pairs.

The work is original and presents a significant advancement in the field of quantum communication. The innovative use of a single optical frequency comb, coupled with a multitude of integrated photonic chips, including lasers and modulators, is a significant demonstration of the potential to develop mass-manufacturable and scalable QKD networks, even for advanced protocols like TF-QKD.

We are deeply grateful to the referee for their time, expertise, and thoughtful review of our manuscript. Their insightful and constructive comments have been invaluable in improving our work. In the revised manuscript, we now have carefully addressed all the referee's comments and suggestions. We particularly appreciate the referee's constructive feedback, especially regarding the significance of clarifying the number of QKD transmitter chips implemented in the network, and the suggestion to characterise a more balanced QKD system with long downstream and upstream fibres. We have now provided a detailed clarification in our response letter and revised the manuscript accordingly.

*To address these points experimentally, we have reimplemented the entire TF-QKD network using **20 real TF-QKD chips** (see revised Fig. 1c) and have recollected nearly **all experimental data** in Fig.2, Fig.3, and Fig.4 of the main text, Extended Data Fig.1, along with additional supporting data in the Supplementary Information. As the referee suggested, we have now reimplemented **paired TF-QKD between two InP chips with long downstream and upstream fibres**, and the results have also been included in Fig.3 and Fig.4.*

We sincerely believe that the referee's suggestions and comments have greatly enhanced the clarity and rigour of our manuscript, and we are thankful for the opportunity to strengthen our work.

The manuscript is clearly written, with some points (presented below) which can be improved. The methodology and data analysis is generally sound, although some parts need to be clarified.

The use of uncertainties is generally correct, although some measured quantities are missing the relative uncertainty. As an example the measured D1, D2 and D3 are missing the uncertainties as well as table S3.

We thank the referee for identifying the missing experimental uncertainty analysis. We have carefully reviewed the manuscript (including D1, D2 and D3, and table S3) to ensure accurate data presentation with uncertainty analysis.

Regarding the manuscript, I have the following comments:

- In both the abstract and in the introduction, the use of the term "photonic QKD network," combined with the intrinsic star topology of the network, may confuse the reader into thinking that full mesh connectivity between the different users has been shown, while in the experiment only pairwise links have been realized thanks to wavelength multiplexing. For the sake of clarity, I suggest that the authors better clarify this point.

We appreciate the referee's valuable suggestion regarding the need for precise terminology when describing our network architecture. In response, we have revised all relevant descriptions throughout the manuscript to clarify that the implemented system establishes pairwise connections between QKD chips, rather than a fully connected star network.

In the revised Abstract, we have rephrased the sentence as: "We sequentially implement pairwise QKD across twenty client-chips through ten wavelength-multiplexed channels, with each surpassing the repeaterless bound at 370 kilometres in spooled fibre, achieving a networking capability (client-pairs $\times$ communication-distance) of 3,700 kilometres."

In the revised Introduction, we have now added a sentence: "We implemented the pairwise TF-QKD between 20 InP client chips through 10 wavelength-multiplexed channels aligned with microcomb lines, realising a total network spanning capability $NL/2 = 3700$ km (where $N=20$, $L=370$) without any trusted relays."

On page 4 of the revised main text, we have added: "Twenty InP chips (footprint 4.6×2 mm² each, see Fig.2i) are divided to group A and group B, to implement pairwise TF-QKD between the two chips $\{A_i, B_i\}$, where $i = [1, 2, \dots, 10]$ represents paired-users sharing identical wavelengths λ_i ."

In the Fig.3 caption, we have now added: "Experimental characterisation of phases across the fibre links between those 10 pairwise client-chips $\{A_i, B_i\}$ and the server chip: "... Data were collected sequentially for each pairwise connected QKD chips at their wavelength channel, while maintaining continuous operation of all other wavelength channels multiplexed in the same fibres."

In a new Supplementary Section 5.2, we have included a discussion on potential extensions to fully connected networks using quantum frequency shifting, as detailed in our response to the referee's next comment.

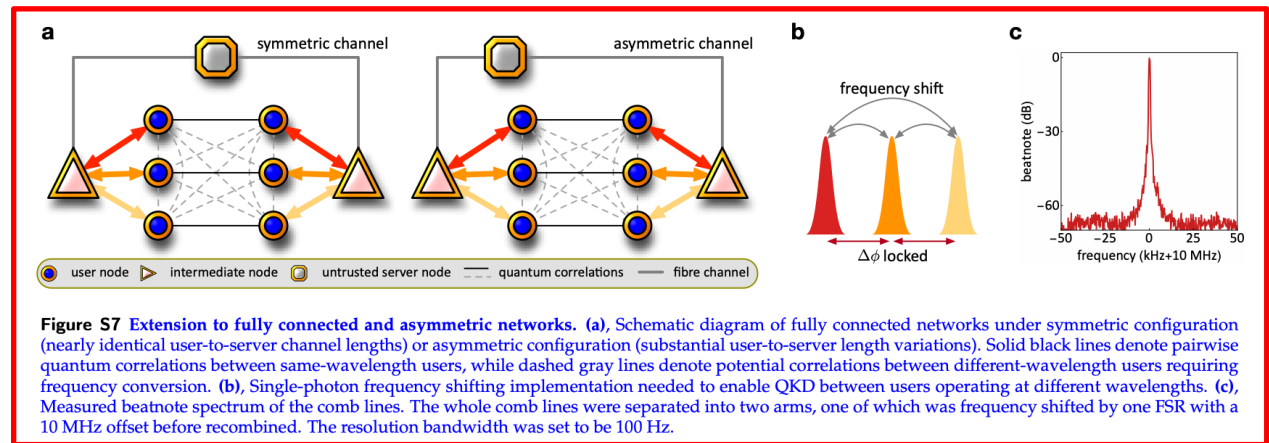
- In the introduction, the authors briefly mention that frequency shifting would be "required for those users with different wavelengths." To enhance the completeness of the work, it would be beneficial if the authors could elaborate further on this aspect. Specifically, could they provide more detail on how frequency shifting would be implemented in this network architecture, and perhaps discuss any potential penalties, such as increased losses, associated with this frequency shifting process?

We agree with the referee that a fully connected quantum network between each user would be important for practical QKD network implementations, and this would likely require a quantum frequency shifting process in our case to improve the completeness of the network with a star topology. We have added a new Fig.S7 to discuss and analyse the possibility. In WDM TF-QKD systems, quantum correlations are established only

between users sharing identical wavelengths. For those users operating at mismatched wavelengths, retrieving relative phase information between optical fields generally remains impossible without additional frequency conversion. To enable such full connectivity, single-photon quantum frequency shifting is demanded, requiring wavelength conversion across tens of GHz to THz. This can be achieved through either electro-optic (EO) or nonlinear-optic approaches with integrated photonics (see Fig.1b). EO-based frequency shifting, implemented via high-speed phase modulation, benefits significantly from thin-film lithium niobate (TFLN) technology, which combines high electro-optic efficiency of >90% shifting efficiency [Nature 599, 587–593 (2021)] with a broad bandwidth of $\pm 641\text{GHz}$ [Light Sci. & Appl. 11, 327 (2022)]. Nonlinear approaches, for example, in PPLN waveguides have demonstrated 55% conversion efficiency [PRL 127, 023602 (2021)] with broadband operation across the C-band [Phys. Rev. Appl. 13, 024017 (2020)], while four-wave mixing Bragg scattering in microresonator-based silicon photonic devices offers an alternative implementation [Nat. Photon. 10, 406–414 (2016) & NJP 21, 033037 (2019)]. However, as the referee pointed out, current implementations face limitations, including significant insertion losses and noise photon generation, restricting their immediate utility in quantum networks.

Achieving stable interference between frequency-shifted optical fields of different wavelengths fundamentally requires maintaining a stable initial phase relationship between the original fields. While multiple independent laser sources (even those with ultra-low intrinsic phase noise) would demand a complex active phase-locking system to synchronise across spectral spans potentially spanning tens of nanometres, the ultra-high coherence microcomb sources utilised in this work provide an inherent solution: **all comb lines naturally preserve stable relative phase relationships throughout the entire spectral range**. This critical advantage is experimentally verified in Fig. S7c, where beatnote measurements between original and frequency-shifted comb lines demonstrate equally narrow linewidths. Advanced microcomb feedback control can enhance comb line phase stabilisation [Nat. Commun. 15, 7030 (2024)], implemented locally at the server node without requiring additional client-side hardware. Alternatively, heterogeneous integration [Nature 620, 78–85 (2023)] offers complementary approaches for improving phase stability.

We have added a new Supplementary Section 5.2 and a new Fig.S7 in the revised manuscript to discuss the possibility and potential penalties, as the referee suggested.



5.2 Fully connected and asymmetric QKD networks

Future real-field implementations of multi-user long-haul quantum communication networks will require flexible configurations, including full connectivity between arbitrary pairs of QKD client chips. In WDM TF-QKD systems, quantum correlations are currently established only between users sharing identical wavelengths, as demonstrated by the black solid lines in Fig. S7a. For users operating at mismatched wavelengths, retrieving relative phase information between optical fields generally remains impossible without additional frequency conversion. To enable such connectivity, single-photon frequency shifting is demanded, requiring wavelength conversion across tens of GHz to several THz, consistent with standard ITU channel spacing in the telecommunications C-band. This can be achieved through either electro-optic (EO) or nonlinear-optic approaches, both compatible with integrated photonic platforms (see Fig.1b). EO-based frequency shifting, implemented via high-speed phase modulation, benefits significantly from thin-film lithium niobate (TFLN) technology⁷⁸, which combines high electro-optic efficiency (> 90% shifting efficiency⁵⁷) with broad operational bandwidth (± 641 GHz⁷⁹). Nonlinear approaches leveraging $\chi^{(2)}$ or $\chi^{(3)}$ processes in periodically poled lithium niobate waveguides have demonstrated 55% single-photon conversion efficiency⁸⁰ with broadband operation across the entire C-band⁸¹, while four-wave mixing Bragg scattering in microresonator-based silicon photonic devices offers alternative implementations^{82,83}. However, current implementations face limitations including significant insertion losses and noise photon generation, restricting their immediate utility in quantum networks.

Achieving stable interference between frequency-shifted optical fields of different wavelengths fundamentally requires maintaining a stable initial phase relationship between the original fields. While multiple independent laser sources (even those with ultra-low intrinsic phase noise) would demand complex active phase-locking systems to synchronise across spectral spans potentially spanning tens of nanometres, the ultra-high coherence microcomb sources utilised in this work provide an inherent solution: all comb lines naturally preserve stable relative phase relationships throughout the entire spectral range. This critical advantage is experimentally verified in Fig. S7c, where beatnote measurements between original and frequency-shifted comb lines demonstrate equally narrow linewidths. Advanced microcomb feedback control can further enhance comb line phase stabilisation⁸⁴, implemented locally at the server node without requiring additional client-side hardware. Alternatively, heterogeneous integration techniques⁸⁵ offer complementary approaches for improving phase stability.

Another critical consideration involves addressing asymmetric channel lengths between users, a key challenge in real-field application. In QKD implementations, channel length asymmetries cause differential loss for quantum states transmitted by different users, requiring protocol parameter optimisation to accommodate these variations⁸⁶. A more immediate challenge arises in experimental implementations:

asymmetric channel lengths eventually form a giant asymmetric MZI, thereby dominating laser phase noise in interference output. While adding compensating fibres to balance arm lengths can improve symmetry²², this approach becomes increasingly impractical in large-scale networks with complex topologies. A more practical approach involves developing laser sources with narrower linewidths. After injection locking at the client nodes, our laser sources exhibit narrow instantaneous linewidths of about 60 Hz. Further linewidth reduction of the microcomb can be achieved by suppressing low-frequency noise components (Fig. 2l) through co-packaging the InP DFB laser with

Si₃N₄ microresonators to mitigate mechanical vibration effects, combined with laser locking to a stable frequency reference. An alternative approach using microresonators with larger modal volumes reduces thermo-refractive noise but compromises FSR, creating deviations from standard ITU channel spacings that require application-specific trade-offs. By synergistically combining these techniques, fully integrated lasers achieving 1 Hz linewidths become feasible⁸⁷, which show the potential to enhance tolerance to channel length disparities in TF-QKD.

• Regarding the spectral stability of the comb, this has been measured for 12 hours and shown in Fig 2g. However, from the figure, it is difficult to appreciate such stability. Can the authors also add a numerical estimate of this stability?

We gratefully acknowledge the referee's comments on microcomb stability characterisation and manuscript clarity. As the referee suggested, we have implemented the following improvements. The 12-hour spectrum (now Fig.2e in the revised manuscript) was captured every minute over 12 hours with an optical spectrum analyser (MS9740A, Anritsu), and we have introduced a new quantitative stability metric (we have now added a new Fig.2f to provide a clearer characterization of the stability), demonstrating excellent intensity stability (0.994 ± 0.006) over the 12-hour measurement period.

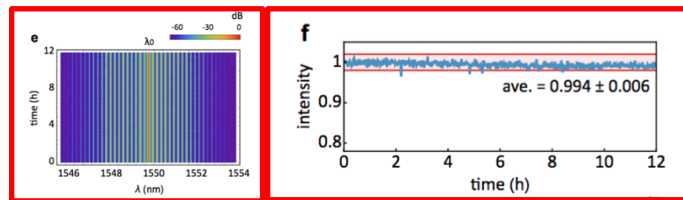


Figure 2...(e) and (f). Spectral stability characterisation of microcomb. The microcomb's spectrum was collected every minute with an optical spectrum analyser over consecutive 12 hours. The normalised intensity fluctuation (f) extracted from (e) shows excellent system stability maintaining a mean relative intensity of 0.994 ± 0.006 .

We have added a detailed description of the stability measurement in [Supplementary Section 4.1](#):

Dark-pulse microcomb generation at the server chip: The Si_3N_4 microresonator and integrated distributed feedback (DFB) laser were mounted on the thermoelectric coolers, respectively with 1 mK temperature control accuracy. The DFB laser chip was controlled by a six-axis stage to precisely adjust the coupling angle and air gap between chips. [Under the condition of small detuning between the laser and](#)

[microresonator's mode](#), we implemented 1 kHz sawtooth-wave current scanning of the DFB laser while performing synchronous coupling air gap adjustments to identify the optimal dark-pulse frequency comb generation regime. This procedure enabled the determination of the optimised laser current and coupling air gap parameters, allowing subsequent turnkey acquisition of the microcomb outputs through direct loading of predetermined current values to the DFB laser under invariant experimental conditions. An optical isolator was inserted at the output of the microcomb to prevent reflected noise light from disturbing the locking condition. Then, part of the microcomb was fed into the photodiode, optical spectrum analyser and phase noise analyser for monitoring and performance characterisation. The desired comb lines ranging from λ_{-5} to λ_{-3} and λ_{+2} to λ_{+8} were selected and intensity equalised with a waveshaper. An Erbium-doped fibre amplifier was used to ensure that the comb had an intensity of at least -20 dBm on-chip power when injected as seed lights onto the QKD transmitter chips. The spacing between different wavelength channels was 30.03 GHz (equal to the FSR of the microresonator), misaligning with the standard ITU channel spacing. Integrated microcombs matching standard ITU channel spacing (e.g., 50/100 GHz) can be readily implemented⁷², enabling full utilisation of mature WDM components for wavelength allocation and spectral filtering. This could facilitate cost-effective deployment in real-field quantum communication networks. After the comb line assignment based on network configuration, polarisation controllers were used to align the polarisation of the seed lights with the optical mode on client chips.

• In the implementation of the decoy state protocol with weak coherent pulses, achieving robust phase randomization is crucial. The manuscript mentions using a single phase modulator for active phase randomization. To provide a more complete picture of the experimental implementation and security analysis, it would be helpful if the authors could clarify a few points regarding phase randomization. Could the authors specify the number of discrete phase levels used for the active phase randomization in their setup? Was the achieved level of phase randomization experimentally characterized or measured? To ensure a comprehensive security analysis, was the potential impact of any imperfect (i.e., discrete rather than continuous) phase randomization considered in the Secure Key Rate (SKR) calculations? If so, could the authors elaborate on how this was accounted for and the magnitude of its effect, if any, on the reported secure key rates?

We thank the referee for highlighting the necessity of clarifying experimental details of phase randomisation using an integrated phase modulator, when implementing the decoy state protocol with weak coherent pulses. In our experiment, the phase randomisation was implemented by applying a single-cycle sawtooth voltage to the phase modulator in each 15 ms quantum encoding period, which covers the whole 2π range. Given the system repetition rate of 200 MHz, it could be regarded as a 3-million-level randomisation, which is sufficient for a proof-of-principle demonstration of decoy state and TF protocols. A discrete level of 12 makes the QKD performance very close to the ideally phase-randomised system [Phys. Rev. Applied 14, 064070 (2020)], so our simplification of the system would still promise a correct result.

In our current experiment, the level of phase randomisation was characterised by interference outcome recording with the server node's SNSPDs for simplicity. Additionally, an intensity monitor photodiode can be added in future to confirm the decoy state intensity before attenuation to the single-photon level, which could be done by the integrated photodiodes on our chip.

As for encoding, the random phase and the encoding phase always work as a whole (Supplementary Section 3.1). We can consider the sawtooth voltage as providing phase randomisation and encoding phase at the same time, which would not affect the result while simplifying the implementation. Statistically, it is equivalent to standard methods that apply random sequences of discrete phase levels as required in practical QKD, because after a mere rearrangement of signals they would become the same. [Thus, statistically, it satisfies the decoy state requirement, and in a proof-of-principle demonstration, it enables accurate inference of single-photon](#)

yields according to standard methods with perfect phase randomisation, to eventually obtain correct secure key rate estimations. In the actual QKD scene, it is necessary to use a truly random phase sequence to avoid a malicious attack by successfully guessing the phase randomisation information, but a simple phase sweeping across a 2π phase range would still yield a proper estimation [Journal of Lightwave Technology, 36, 17 (2018)] in a proof-of-principle demonstration. We have now added those discussions and analyses in [Supplementary Section 4.2](#).

4.2 Phase randomisation for implementing the decoy state method

Phase randomisation is essential for the decoy state method using weak coherent state sources. In the experiment, the random encoded phase $\delta_{A(B)}$ was set by applying a sawtooth voltage on the phase modulator at the client chip, sweeping from 0 to 2π at one quantum key encoding stage (that is, successive 15 ms in the period of 20 ms). Given the system repetition frequency of 200 MHz, an equivalent discrete randomisation level of 3 million was reached. For a proof-of-principle experiment, the preset repeated phase sequence effectively emulates the random phase settings⁷⁴. The random phase and the encoding phase always work as a whole. We can consider the sawtooth voltage as providing phase randomisation and encoding phase at the same time, which would not affect the result while simplifying the implementation. Statistically, it is equivalent to standard methods that apply random sequences of discrete phase levels as required in decoy states and practical QKD. In the actual QKD scene, it is necessary to use a truly random phase sequence to avoid malicious attack by successfully guessing the phase randomisation information, but a simple phase sweeping across 2π phase range would still yield a proper estimation⁷⁴. Moreover, in our current experiment, the level of phase randomisation was characterised by SNSPD photon counting for simplicity. In practical cases, an intensity monitor photodiode can be added to confirm the decoy state intensity before attenuation to a single photon level, which could be done by the integrated photodiodes on our chip.

As the referees suggested, in the revised manuscript, we have now included a new [Supplementary Section 6.1](#) to discuss and analyse the security considerations associated with phase randomisation. [Please also see our response to the referee's comments on security analysis.](#)

- *Decoy state failure:* The decoy-state method has become an essential component of modern QKD systems since its inception. The decoy-state method requires the generation of multiple optical pulse intensities (distinct from the signal level) that are randomly interleaved with quantum signals during transmission. Crucially, these decoy pulses must incorporate random phases to average coherent states to a mixture of photon number states, enabling accurate estimation of single-photon yield and secure key extraction. Deviations between actual and nominal decoy intensities can introduce security vulnerabilities⁸⁸. In our experiment, the random encoded phase was set by applying a sawtooth voltage on the phase modulator on the client chip, which provide an equivalence discrete randomisation level of 3 million effectively emulating the random phase settings⁷⁴ (see Section 4.2). In our experimental implementation, we employ SNSPDs for direct intensity calibration, while practical deployments would require integrated photodiodes to monitor intensity before attenuation to single photon level, which is a capability readily supported by our InP photonic chip design.

- A potentially critical aspect of the experimental setup is the significant difference in length between the downstream fibers used for comb distribution and the upstream quantum communication links. While understandable for a lab demonstration, this asymmetry raises questions about the representativeness of the results for a truly scalable, long-distance network. Specifically, the drastically shorter downstream fibers likely minimize several noise contributions that would become prominent in a deployment with comparable downstream and upstream distances. For instance, what impact would be observed if the downstream channels were also extended to lengths comparable to the upstream links? One could anticipate several potential downsides, such as increased phase noise accumulated along the longer downstream fiber paths, potentially impacting the phase locking stability at the client chips. Another point would be related to higher levels of Raman and scattering noise introduced in the extended downstream fibers, and additional noise due to the increased amplification demands on EDFAs for longer downstream comb delivery. While acknowledging the complexity of implementing fully symmetric fiber lengths across all links, it would significantly strengthen the demonstration to provide evidence, even for a single user pair, of successful operation with comparable downstream and upstream fiber distances.

We thank the referee for insightfully pointing out the necessity and importance of characterising TF QKD with comparable downstream and upstream fibre lengths. In our previous experiment, we intentionally adopted a short downstream fibre for simplifying the proof-of-principle demonstration of a chip-based TF-QKD network. We fully agree with the referee that in future practical applications, such a balanced TF QKD network structure with both long upstream/downstream fibres is unavoidable, although our current work aims for a proof-of-principle demonstration. We also agree with the referee that in the more balanced upstream/downstream TF QKD scenario, some impacts of using long downstream fibres have to be considered, including: (i) attenuation of downstream light intensity, requiring additional EDFA amplifications of comb lines, which could introduce ASE and degrade the optical injection-locking (OIL) performance. (2) long optical path in the giant closed-loop MZI results in accelerated phase shifts accumulation in the fibre, (3) Raman and scattering noises.

As suggested by the referee, **we have now implemented several new experiments with long downstream fibres.** Limited by experimental resources in our lab, we used up to 120 km-long downstream servo fibre, not that long, but it is sufficient to test noises, OIL phase tracking, and QKD performance. The upstream fibre length was maintained as 370 km (185 + 185 km), while the downstream fibre was extended to 120 km (60 + 60 km) for implementing TF-QKD.

These new experiments were implemented and have now been added to the revised manuscript:

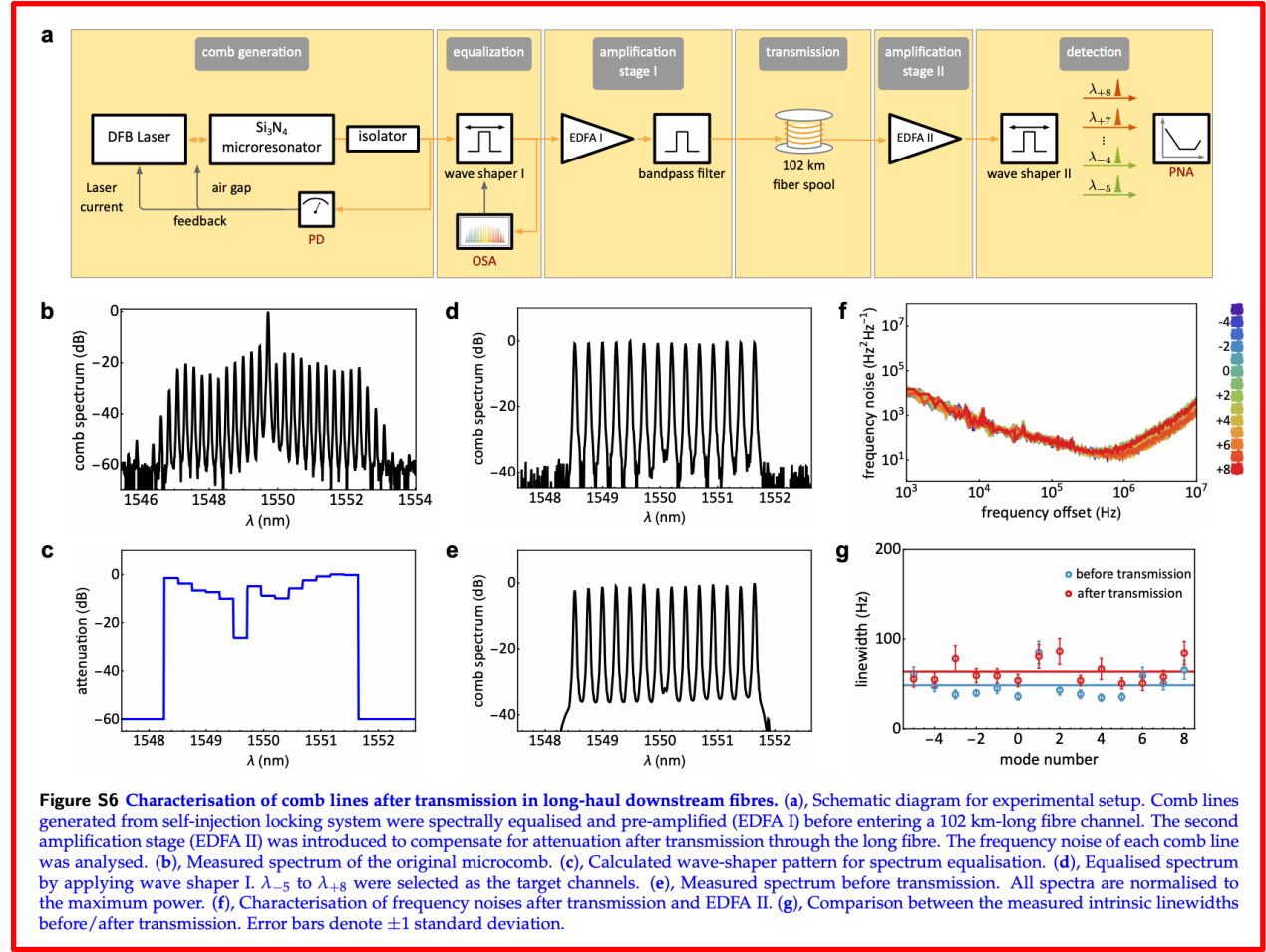
(i) full classical characterisations of local OIL lasers' frequency noise, when all microcomb lines seeding light were sent through long 102 km servo downstream fibres and reamplified by EDFAs. There was no obvious performance degradation observed for all 13 wavelength channels. Excess noise added by ASE of EDFA and Raman effect in the long downstream fibres can be effectively suppressed by introducing additional optical filters before entering the client chips. **These results are reported in the new Fig.S6. These results show nearly the same linewidth before/after transmission through the channel for all 13 wavelength channels (Fig.S6g).**

We have added a new Supplementary Section 5.1 "Network with symmetric upstream-downstream channels".

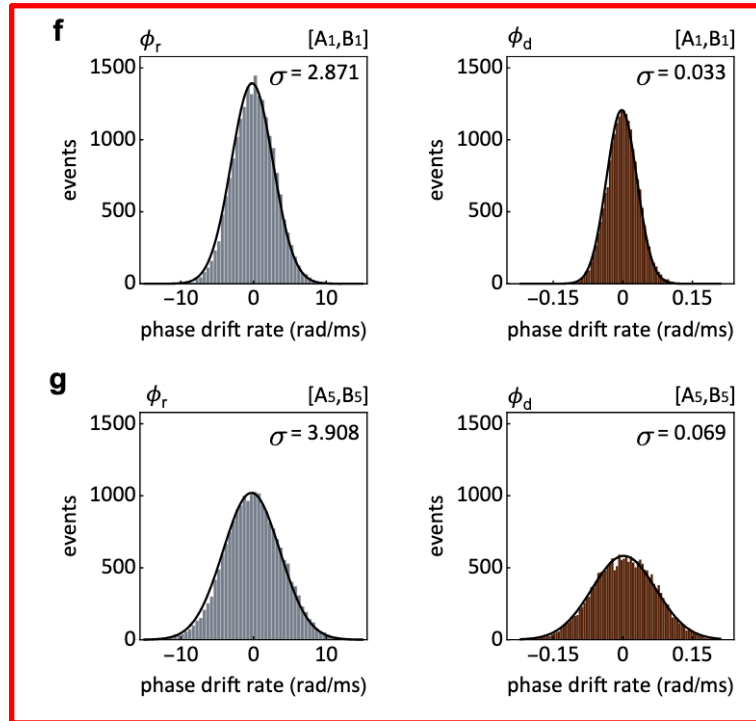
5.1 Network with symmetric upstream-downstream channels

In this section, we present TF-QKD with extended fibre lengths for both the downstream (server-to-client) and upstream (client-to-server) channels. As a proof-of-principle test, we implemented a 102 km downstream fibre link. This introduces approximately 20 dB attenuation of the comb lines, necessitating amplification to maintain sufficient optical power for injection locking at client chips. The amplification process introduces several noise sources that may degrade system performance, including ASE from EDFAs, phase fluctuations induced by long-haul transmission, and nonlinear effects. To characterise the system performance, we constructed the experimental setup shown in Fig.S6a. The generated microcomb first underwent spectral equalisation via a programmable filter (wave shaper I) to normalise power across all wavelength channels (Figs. S6b-d), ensuring uniform gain and SNR for each comb line (λ_{-5} to λ_{+8}). The attenuation pattern uploaded to the wave shaper I was calculated in Fig. S6c. Pre-transmission amplification (EDFA I) was carried out to ensure sufficient input power for the second stage amplification after long fibre transmission (-40 dBm minimum input power per comb line required for low-noise amplification) while maintaining total fibre input below 0 dBm (-11 dBm per comb line) to suppress nonlinear effects. A bandpass filter (about 450 GHz) reduced ASE noise before fibre transmission (Fig. S6e). After post-transmission amplification (EDFA II), we analysed individual comb lines via wave shaper II filtering. The power spectral densities (Fig. S6f) confirm preserved low-noise characteristics across all channels. Comparative linewidth measurements before/after transmission (Fig. S6g) show only minor degradation, attributable to slight SNR reduction. These results verify that proper power management and filtering can maintain comb line quality despite two-stage amplification.

Notably, EDFA-based downstream amplification is well-established in TF-QKD implementations^{20,49,75}. The remaining consideration for extended downstream fibres is additional phase noise. Since the optical injection-locking at the client nodes nearly perfectly replicates the frequency and phase of the seed light, when the upstream and downstream channels are equal in length, the entire process can be considered equivalent to a larger-scale MZI with each arm length doubled compared to the original configuration. Notably, phase tracking remains feasible even for fibre spans exceeding 1,000 kilometres²⁰. Furthermore, in field deployments, it may benefit from partial noise cancellation due to uncorrelated environmental perturbations e.g., vibration and temperature fluctuations) along extended fibres^{19,77}. Consequently, extending the downstream fibre channel is not expected to impose additional challenges for phase tracking. Our experimental implementation (as reported in Figs.3-4, main text) successfully demonstrates efficient phase tracking and SNS-TF-QKD in this symmetric long-haul configuration, validating the feasibility of balanced upstream-downstream quantum communication.



(ii) full quantum characterisation of phase tracking and TF-QKD between two InP client chips (indicated by {A5, B5}, as an example) with 60+60 km downstream fibres, where dual- λ microcomb lines seeding light were sent through two 60 km downstream fibres, amplified by EDFAs and injected into two local InP lasers. **These new results in Fig.3g in the revised main text show a similar phase drift rate in 120 km long fibres and short fibres, which verifies the effectiveness of OIL on the local InP chips, and more importantly, validates phase tracking in TF-QKD systems with long upstream/downstream fibres. Note that slightly faster phase shifts in the long channel could be effectively tracked by adjusting the relative phase recalibration period in this case (5 ms out of 20 ms $\rightarrow$ 2 ms out of 5 ms). In the new Fig.4, we also measured the QBER and secure keys for the network employing short and long downstream fibres. These results in the updated Fig.4 imply similar performances of QBER and secured keys by using the short and long fibres.**



In the Fig.3 caption, we have now added: *"The fibre network employed 370 km upstream (185+185 km) and predominantly short downstream links, except for the {A5, B5} paired QKD which adopted 120 km downstream fibres. Phase information was extracted via SNSPD-based single-photon interference measurements (10 kHz sampling rate). Data were collected sequentially for each pairwise connected QKD chips at their wavelength channel, while maintaining continuous operation of all other wavelength channels multiplexed in the same fibres. (e). An example of phase distributions for the {A1, B1} paired QKD chips. Inset: zoom-in view of the initial 100 ms window. (f) and (g), Measured phase drift rate: (f) $\Phi_r = 2.871$ rad/ms and $\Phi_d = 0.033$ rad/ms for short downstream links {A1, B1}, and (g) $\Phi_r = 3.908$ rad/ms and $\Phi_d = 0.069$ rad/ms for long downstream links {A5, B5}. These results verify effective injection locking on local QKD chips and robust phase tracking in TF-QKD systems, with long-haul upstream and downstream fibres"*

In the Fig.4 caption, we have now added: *"(b) and (d), Segmented QBER in the X-basis and their statistical distributions in the 370 km upstream channels. Each data point represents the error rate measured by sending a total of 150×10^6 bins. The network employed short downstream fibres, except for the {A5, B5} with 120 km downstream fibres."*

In the revised main text page 6, we have added: *"For experimental simplicity, short downstream fibres were used in above measurement, except for the {A5, B5} user pair where 120 km (60 + 60 km) fibres were used to characterise the network with realistic long downstream fibres. We characterised injection locking and frequency noise, when combs were transmitted through long downstream fibres and consecutively reamplified (see Fig.S6), achieving comparable performance to short-haul configurations. In Figs. 3f,3g, comparative results reveal accelerated phase drift in long downstream fibres (see ϕ_d, ϕ_r for {A1, B1} and {A5, B5}). This behaviour emerges from the formation of a giant interferometer, where injection-locked lasers replicate the seed light's phase information. Despite increased drift, phase tracking can be achieved by simple adjustment of phase correction"*

cycles as the following: Φ_d was recalibrated every 2 ms (5 ms cycle) for {A5, B5} versus every 5 ms (20 ms cycle) for other pairs."

In the Supplementary information Section 4 "WDMed Quantum channels in fibres", we have added more details:

WDMed Quantum channels in fibres: The reference and quantum signals were wavelength-multiplexed and transmitted in the long-haul upstream fibre spool back to the server node simultaneously. The upstream channel distance from Alices' and Bobs' node to the central server node and corresponding fibre losses are provided in Table S3. Constrained by limited RF resources, we simulated concurrent multi-user communication by implementing the whole quantum state encoding procedure in sequence for the selected user pair while leaving other non-target wavelength signals unmodulated and directly injecting into the upstream fibre channels. To evaluate worst-case crosstalk, these non-target wavelength signals were maintained at maximum intensity levels required for phase tracking (see Section 4.3). To simplify the system for a proof-of-principle demonstration of TF-QKD network, the downstream fibres from the microcomb to the QKD client-chips were replaced by short fibres in most cases, except for the user pair {A₅, B₅}, where 120 km-length (60+60 km) downstream fibres were used. We confirm comparable phase drift and phase tracking for short and long downstream fibres in Fig.3 and implement TF-QKD in both cases in Fig.4. Detailed performance characterisation regarding the introduction of long downstream fibres is presented in the main text and further discussed in Section 5.1.

• Regarding synchronization, it is not clear to me whether this is achieved optically with the disseminated comb lines or using external RF signals. From the main text, it appears that the comb lines are also used for synchronization; however, in the supplementary figure (S3), synchronization looks like it is performed using RF cables. Is this the case? What would be the impact of also performing the synchronization using the downstream/upstream link? This point would be required for a real in-field implementation.

We thank the referee for their insightful comments regarding synchronisation implementation. In our current experiment, we employed RF-based synchronisation via electrical signals to minimise system complexity, as shown in Fig. S3.

In the revised main text Page 6, we have added a sentence: *"Device clocks were currently synchronised via electrical signals (see Fig.S3), while in future microcomb could enable practical clock synchronisations."*

In the revised main text Page 6, we have now added a sentence: *"Phase tracking and key distribution were sequentially executed between paired chips {A_i, B_i} due to resource constraints in electronic controls and synchronisations."*

In the revised main text, we have now removed all unclear descriptions of optical synchronisation using comb lines to avoid misleading.

We fully agree that optical synchronisation is critical for real-world deployment. Recent advances demonstrate successful optical clock synchronisation in quantum networks [see Nature 640, 911–917 (2025)]. In future, it is possible to leverage dark-pulse microcomb for integrated optical synchronisation, since these microcombs exhibit exceptional coherence and can simultaneously serve as optical synchronisers and RF synthesisers [see our recent work in Nat. Electron. 8, 322–330 (2025)]. This approach would enable fully optical synchronisation while maintaining the TF QKD system's functionality. In the current demonstration, we prioritised simplicity in the QKD implementation by RF synchronisation in the laboratory.

We have now also added a detailed discussion of optical synchronisation prospects in Supplementary Section 4.1 "Single-photon detection at the server node".

of all dynamic control and detection components were precisely synchronised using electrical signals. In addition, optical frequency comb has been commonly used in both classical and quantum communication networks²², and thus integrated microcomb could be used for clock synchronisation in the QKD network. In future, it is possible to leverage dark-pulse microcomb for integrated optical synchronisation, since these microcomb exhibit exceptional coherence and can simultaneously serve as optical synchronisers and RF synthesizers⁷³. This approach would enable fully optical synchronisation while maintaining the TF QKD system's functionality.

• *I am wondering if the distribution of the comb lines from Charlie to the users can open side-channel attacks, such as wavelength shift attacks or trojan horse attacks. Could the authors comment on this point?*

We thank the referee for pointing out the necessity of discussing potential vulnerabilities introduced by optical injection locking technique. In the revised manuscript, we have added a **Supplementary Section 6.1** to provide a regular security analysis for MDI-type QKD from the aspects of decoy state failure, side channel leakage, active attacks from the output port and photon statistics altering attack. Then, in a **Supplementary Section 6.2**, we first identify how those security analyses apply to optical injection-locking systems.

6.1 Regular security analysis of QKD transmitters

We here discuss the transmitters' security in standard BB84-like or original MDI-QKD implementations, which generally operate without OIL. Our SNS-TF-QKD transmitter design shares core structural elements with these transmitters, differing primarily in the signal encoding strategy (sending/not-sending basis). Accordingly, we examine three critical loophole categories: decoy state failure (source-level imperfections), side-channel leakage (modulator-related information leakage), active output-port attacks (output port information leakage).

- *Decoy state failure:* The decoy-state method has become an essential component of modern QKD systems since its inception. The decoy-state method requires the generation of multiple optical pulse intensities (distinct from the signal level) that are randomly interleaved with quantum signals during transmission. Crucially, these decoy pulses must incorporate random phases to average coherent states to a mixture of photon number states, enabling accurate estimation of single-photon yield and secure key extraction. Deviations between actual and nominal decoy intensities can introduce security vulnerabilities⁸⁸. In our experiment, the random encoded phase was set by applying a sawtooth voltage on the phase modulator on the client chip, which provide an equivalence discrete randomisation level of 3 million effectively emulating the random phase settings⁷⁴ (see Section 4.2). In our experimental implementation, we employ SNSPDs for direct intensity calibration, while practical deployments would require integrated photodiodes to monitor intensity before attenuation to single photon level, which is a capability readily supported by our InP photonic chip design.
- *Side-channel leakage:* Side-channel vulnerabilities arise from non-ideal device performance, where secret information becomes correlated with unwanted degrees of freedom or unintended carriers^{89,90}. These problems are usually specific to the system implementation, and needs to be dealt with case-by-case. In our system, leakage from unwanted wavelengths and time windows can be considered negligible. Although the entire comb is transmitted to users, they only filter out a single wavelength to inject into the transmitter laser, and due to its mode competition, the side mode suppression ratio is sufficiently high to suppress emissions at other wavelengths. With the high extinction ratio of the MZIs, photon emission in non-signal time windows is low enough to ensure information security. Leakage from unused polarisation could occur if the signal state intensity is calibrated for a specific polarisation state, and residual photons with an orthogonal polarisation state also undergo encoding modulation. A polarisation filter would enhance security. Another form of side-channel leakage arises from the pattern-dependent effects in InP-based EO modulators or system misalignment, which could enable adversaries to predict subsequent signals based on previous ones or detect anomalous signal behaviour caused by modulator-induced patterns^{91,92}. This issue does not arise in our case since we employ repetitive signal pulses that form no discernible pattern. For practical QKD applications, high modulator bandwidth and precise calibration are required, which are readily met using on-chip modulators.
- *Active output-port attacks:* Active attacks targeting transmitter output ports represent the most concerned type of security threat, as they can create fatal loopholes even in well-calibrated QKD systems that have addressed conventional implementation flaws. These attacks typically require injecting exterior light into the transmitter. Fortunately, such threats can be effectively mitigated through sufficient optical isolation at the output port⁹³. In our case, given the fundamental upper bound on optical power in fibre channels, we can establish a practical isolation threshold beyond which active attackers cannot exploit residual leakage or device behaviour modifications. By adding sufficient isolators and WDMs, the system can achieve the necessary isolation level while preventing wavelength-based security vulnerabilities. This complete isolation implementation represents standard practice for deployments.

In **Supplementary Section 6.2**, we then discuss and analyse a distinct class of attacks, which is the **photon statistics altering attack**. Using an independent laser for the transmitter and performing injection locking rather than a mere EDFA or other types of optical amplifier is partially motivated by avoiding such attack. In a photon statistics altering attack, an eavesdropper modifies the photon number distribution of signal pulses away from the Poisson distribution while preserving the average intensity, thereby causing a false estimation of the single-photon component. According to the decoy-state methods, only bits carried by single-photon components are considered secure. By transmitting quantum signals with varying intensities, we can estimate the actual number of single photons reaching the receiver and subsequently extract secure bits through privacy amplification. While the estimation is based on the Poisson distribution of photon number in the decoy and signal states, often only the average intensities of them are set and monitored in the QKD implementation. Therefore, a light source guaranteeing Poissonian photon statistics is essential for TF-QKD. This requirement

favours a private laser at the user nodes instead of plug-and-play configurations, as the latter may compromise statistical integrity and needs extra effort to maintain its security. In our experiment, **the regeneration of low-noise laser light on the local client chip (achieved by injection-locking slave DBR lasers to microcombs) provides a solution for implementing private lasers with Poissonian photon statistics.** This approach avoids directly using the microcomb output, which would otherwise remain vulnerable to photon-statistics-altering attacks. Nevertheless, even with a private laser, an adversary could potentially alter the photon number distribution through manipulated injection light. While adding a photon-number-resolving detector at the injection port could address this vulnerability, this approach would be prohibitively expensive for practical implementations. A more feasible solution is to operate in the weak-injection regime. This ensures the user's source maintains Poissonian photon statistics with negligible deviation while still enabling effective OIL at low injection power levels. Alternatively, increasing the user laser's intensity followed by attenuation provides another viable approach, as strong attenuation drives any photon number distribution toward a Poisson distribution.

However, a comprehensive security analysis of TF-QKD systems employing OIL remains lacking. While our investigation has not identified any significant exploitable vulnerabilities in the current implementation, potential security loopholes may still exist. Future research may uncover new attack vectors, potentially necessitating system modifications to maintain robust security.

6.2 OIL security analysis

The seeding light from the central microcomb facilitates the regeneration of distant coherent optical fields for TF-QKD. However, implementing OIL requires allowing external light to enter the transmitter, which may introduce practical security concerns since potential active

attacks might exploit the same pathway. Additional safeguards are required to mitigate these vulnerabilities. In our experiment, the injection light enters through the rear facet, preserving the front facet's isolation integrity. Consequently, any additional vulnerabilities introduced by OIL can be effectively attributed to the light source itself, specifically, the DBR laser on the QKD client-chips.

In fact, assuming that robust security countermeasures are implemented at the transmitter output as discussed in Section 6.1, most optical injection threats will automatically fail. Attacks targeting the light source can either modify the original carrier's intensity and/or phase or introduce new carriers that might escape with undetected encoded information. These attack vectors closely resemble those described in the previous Section 6.1: carrier modification could compromise decoy-state protocols, while introduced carriers might create side-channel leakage. However, these vulnerabilities can be effectively mitigated through proper countermeasures. By implementing a narrow-band optical filter, a spatial and polarisation mode cleaner to reject any unwanted carrier, and an optical power monitoring system with appropriate bandwidth (and resistant to blinding attacks) along with active randomisation using a calibrated phase modulator to ensure proper definition of encoded signals, we can reduce information leakage to negligible levels. That being said, yield reduction due to signal interception of the adversary or the strong device disturbance imposed by active attacks may still lead to a lower key rate, similar to the effect of an adversary simply severing the fibre channel between users.

There is a special class of attacks that is available due to the OIL scheme: photon statistics altering attack⁹⁴, which could be classified as a Trojan horse attack. Using an independent laser for the transmitter and performing injection locking^{22,30,31,47}, rather than a mere EDFA or other types of optical amplifier is partially motivated by avoiding such attack. In a photon statistics altering attack, an eavesdropper modifies the photon number distribution of signal pulses away from the Poisson distribution while preserving the average intensity, thereby causing a false estimation of single-photon component. According to decoy-state protocols, only bits carried by single-photon components are considered secure. By transmitting quantum signals with varying intensities (each exhibiting different single-photon component proportions), we can estimate the actual number of single photons reaching the receiver and subsequently extract secure bits through privacy amplification. While the estimation is based on the Poisson distribution of photon number in the decoy and signal states, often only the average intensities of them are set and monitored in the QKD implementation. Therefore, a light source guaranteeing Poissonian photon statistics is essential for TF-QKD systems. This requirement favours a private laser at the user nodes over plug-and-play configurations^{16,95}, as the latter may compromise statistical integrity and needs extra effort to maintain its security. In our experiment, the regeneration of low-noise laser light on the local client chip (achieved by injection-locking the slave DBR lasers to the microcomb) provides a solution for implementing private lasers with Poissonian photon statistics. This approach avoids directly using the microcomb output (with amplification), which would otherwise remain vulnerable to photon-statistics-altering attacks. Nevertheless, even with a private laser, an adversary could potentially alter the photon number distribution through manipulated injection light. While adding a photon-number-resolving detector at the injection port could address this vulnerability, this approach would be prohibitively expensive for practical implementations. A more feasible solution is to operate in the weak-injection regime. This ensures the user's light source maintains Poissonian photon statistics with negligible deviation while still enabling effective OIL at low injection power levels⁹⁶. Alternatively, increasing the user laser's intensity followed by attenuation provides another viable approach, as strong attenuation drives any photon number distribution toward a Poisson distribution⁹⁷.

In summary, currently, a comprehensive security analysis of QKD systems employing OIL remains lacking. While our investigation has not identified any significant exploitable vulnerabilities in the current implementation, potential security loopholes may still exist, particularly those applicable to general QKD transmitters that could also affect TF-QKD transmitters. Future research may uncover new attack vectors, potentially necessitating system modifications to maintain robust security.

• From my understanding, the phase tracking with the comb lines works well if the two channels between Alice-Charlie and Bob-Charlie are symmetric; however, asymmetries in the channel, due to the finite frequency and phase stability, can degrade the phase tracking. Can the authors comment more on this point? If this is a problem for asymmetric channels, how can it be solved?

We thank the referee for raising this important point regarding phase tracking in asymmetric channels between Alice-Charlie and Bob-Charlie. Indeed, such asymmetries of channels can occur in practical systems, and it may degrade performance due to frequency and phase instability, as the referee correctly pointed out. Successful phase tracking in asymmetric configurations requires those lasers with ultra-low phase noise.

The characterisation of the stability in the self-injection-locking dark pulse generation was discussed in a new Fig.2f and in the revised Supplementary Section 4.1 “Dark-pulse microcomb generation at the server chip” (see our response to the referee’s comment on stability).

Our current microcomb lasers exhibit non-negligible low-frequency noise, which poses challenges for directly implementing asymmetric TF QKDs. In the new Supplementary Section 5.2 of the revised manuscript, we have identified several promising solutions to achieve ultra-low phase noise. Optimising our system using state-of-the-art techniques, such as fully packaged self-injection-locked microcombs or fully integrated microcombs, could achieve Hz-level linewidths. Very recently, it shows that integrating photonic chips with microfabricated reference cavities could enable mHz-linewidth lasers (with a 150-Hz integral linewidth) [Nat. Photon. (2025), DOI:10.1038/s41566-025-01701-5]. We have added a new Supplementary Section 5.2 discussing these promising approaches for asymmetric TF-QKD implementation.

Another critical consideration involves addressing asymmetric channel lengths between users, a key challenge in real-field application. In QKD implementations, channel length asymmetries cause differential loss for quantum states transmitted by different users, requiring protocol parameter optimisation to accommodate these variations⁸⁶. A more immediate challenge arises in experimental implementations:

asymmetric channel lengths eventually form a giant asymmetric MZI, thereby dominating laser phase noise in interference output. While adding compensating fibres to balance arm lengths can improve symmetry²², this approach becomes increasingly impractical in large-scale networks with complex topologies. A more practical approach involves developing laser sources with narrower linewidths. After injection locking at the client nodes, our laser sources exhibit narrow instantaneous linewidths of about 60 Hz. Further linewidth reduction of the microcomb can be achieved by suppressing low-frequency noise components (Fig. 2l) through co-packaging the InP DFB laser with

Si₃N₄ microresonators to mitigate mechanical vibration effects, combined with laser locking to a stable frequency reference. An alternative approach using microresonators with larger modal volumes reduces thermo-refractive noise but compromises FSR, creating deviations from standard ITU channel spacings that require application-specific trade-offs. By synergistically combining these techniques, fully integrated lasers achieving 1 Hz linewidths become feasible⁸⁷, which show the potential to enhance tolerance to channel length disparities in TF-QKD.

A relevant point: we would like to emphasise that our streamlined approach that combines dual- λ methods and microcomb-enabled coherent WDM can simplify phase tracking, providing an efficient solution for multi-wavelength, multi-user, long-haul TF-QKD network. In our network configuration in Fig.1d, users within the same metropolitan zone share common upstream/downstream backbone fibres (spanning 100s of kilometres) connecting the server and intermediate nodes, while requiring dedicated short-reach fibres between client nodes and the intermediate node, resulting in each client-server connection comprising both shared long-haul and short fibre segments. When these dedicated fibres are sufficiently short with slow phase drift rates, metropolitan users can share a common reference wavelength (because of the locked phases between all comb bins generated by the same high-stability microcomb) for phase tracking instead of requiring individual reference wavelengths. Phase postselection implementation announces all reference wavelength phase shifts, enabling neighbouring users to select appropriate phase windows for data sifting. When the dedicated fibres’

length becomes excessive, the phase drifts accelerate, necessitating separate reference and quantum wavelengths for each user. For our experimental demonstration under stable laboratory conditions, we employed a common reference wavelength λ_0 with sequential phase tracking for user pairs while maintaining all other quantum signal transmissions (without detection). The statistical characteristics of phase shifts in the fibre spools demonstrated temporal stationarity (see new results in Fig.3), thereby validating this method for evaluating simultaneous phase tracking across all communication channels.

We have added a sentence in the main text Page 6: *"Our implementation combines established dual- λ phase tracking and postselection..., with microcomb-enabled coherent WDM, which together provide an efficient solution for QKD network."*

We have significantly revised Supplementary Section 4.3 to explain the dual-lambda phase tracking method:

4.3 Global phase tracking with dual- λ method

The raw key obtained from the interference at the server node hinges on ensuring that it receives the signals as anticipated by users, notwithstanding the various signal degradations over long fibres. The primary factor influencing the interference result is the fluctuation of the relative global phases between Alice and Bob, which can be ascribed to phase noise from lasers and accumulated phase shifts in the fibres:

$$\Delta = \phi_A - \phi_B = \Delta_{\text{laser}} + \Delta_{\text{channel}}. \quad (\text{S23})$$

In this work, the upstream and downstream channels form a large-scale closed MZI for the signal transmission. The adoption of ultra-low-noise lasers by injection locking local DBR lasers to microcomb lines, the laser phase noise Δ_{laser} can be significantly reduced. We adopted the dual- λ method to track and estimate phase shifts in channels Δ_{channel} by comparing co-propagating wavelengths, retrieving only residual slow fluctuations undergoing the same fibre. The dual- λ method also helps diminish the noise stemming from double-Rayleigh scattering in the time-multiplexing scheme and enhances the signal duty cycle^{18,75}.

The system tracks global phases between users but without performing active compensation. These global phases act on the user-encoded optical fields and ultimately determine the long-distance single-photon interference visibility (see Eq. S16). The ultimate phase interval selection in the X-basis depends on the combined effects of $\{\delta_A, \delta_B, \phi_A, \phi_B\}$. Because the values of randomly chosen $\{\delta_A, \delta_B\}$ are announced publicly for verification, the difference between (i), real-time compensation of the global phases or (ii), real-time tracking with postselection (which is the case in this work) is whether $\phi_B - \phi_A$ could be regarded as a constant preset value $\Delta(t) = \Delta(0)$ or time-varied known value $\Delta(t)$. Both approaches ensure uniform phase distribution in $[0, 2\pi)$ of the total relative phases, because the global phases Δ follow the uniform temporal distribution. Therefore, both phase compensation and postselection methods yield identical proportions of effective events satisfying Eq. S16, with no additional event loss. Both global phase compensation^{18,19,21} and postselection^{20,48,49} have been widely implemented in TF-QKD experiments. Phase postselection can simplify the system by eliminating feedback loops. In this work, we intentionally adopted phase postselection to streamline system complexity, focusing on demonstrating scalable integrated photonic hardware for TF-QKD networks. That being said, regarding key rate performance, there is no fundamental difference between using post-selection or phase compensation since phase randomisation (required for decoy-state protocols) inherently involves post-selection in X_{11} -basis. However, for field-deployed QKD systems, phase compensation offers a practical advantage by eliminating the additional data sifting step required in post-selection approaches. In such implementations, phase compensation methods can be independently applied in fibre channels.

In our network configuration in Fig.1a, users within the same metropolitan zone share common upstream/downstream backbone fibres (spanning hundreds of kilometres) connecting the server and intermediate nodes, while requiring dedicated short-reach fibres between client nodes and the intermediate node, resulting in each client-server connection comprising both shared long-haul and short fibre segments. When these dedicated fibres are sufficiently short with slow phase drift rates, metropolitan users can share a common reference wavelength (because of the locked phases between all comb lines generated by the same high-stability microcomb) for phase tracking instead of requiring individual reference wavelengths. Our phase postselection implementation announces all reference wavelength phase shifts, enabling neighbouring users to select appropriate phase windows for data sifting. When the dedicated fibres' length becomes excessive, the phase drifts accelerate, necessitating separate reference and quantum wavelengths for each user. For our experimental demonstration under stable laboratory conditions, we employed a common reference wavelength λ_0 with sequential phase tracking for user pairs while maintaining all other quantum signal transmissions (without detection). The statistical characteristics of phase shifts in the fibre spools demonstrated temporal stationarity (see results in Fig.3), validating this method for evaluating simultaneous phase tracking across all channels.

We clarify and summarise several characteristics of the entire phase-locking system, from the server chip's self-injection locking microcomb to user chips' injection-locking lasers, and phase tracking in the fibre channels. 1), The self-injection locking microcombs exhibit exceptional stability and superior performance. 2), The local slave lasers, phase-locked with the microcombs through injection-locking, also show high resilience to perturbations commonly encountered in standard monolithic devices, such as those induced by back-scattering to the DBR lasers. In addition, fluctuations in seed light intensity can be effectively re-stabilised at the user chips³⁰, with minimal impact on laser output intensity. Phase-locking of server's microcomb lasers and clients' slave lasers refers to the suppression of phase noises, which are characterised by frequency noises spectra and linewidths, as reported in Fig. 2 of the main text. 3), In quantum channels connecting the server node and client nodes, our streamlined approach that combines dual- λ methods and microcomb-enabled coherent WDM techniques (see the above paragraph), simplifies phase tracking and locking by obviating the need for intricate electronic controls, redundant ultra-stable cavities, and complicated phase controls in the channels. The microcomb-driven integrated photonic devices enable reliable transmission across WDM quantum channels, thereby providing an efficient solution for multi-wavelength, multi-user and long-haul TF-QKD networks.

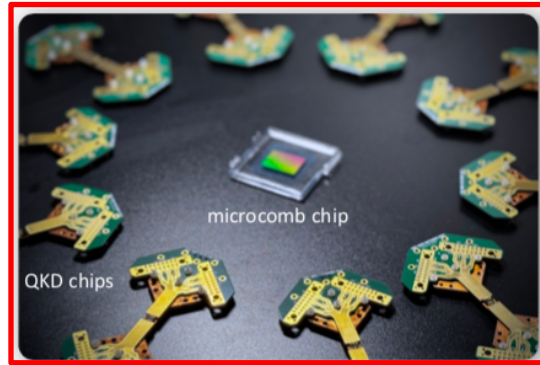
• It is not completely clear to me if the 10 pairs of links are performed in parallel at the same time with sharing of some common fiber, or are independently and sequentially performed. Can the authors clarify this point?

We appreciate the referee's highly constructive feedback regarding [the significance of clarifying the number of QKD transmitter chips implemented in the network and how they were implemented](#). To address these points experimentally, we have reimplemented the entire TF-QKD network using **20 real TF-QKD chips** (see revised Fig. 1c) and have recollected nearly **all experimental data** in Fig.2, Fig.3, and Fig.4 of the main text, Extended Data Fig.1, along with additional supporting data in the Supplementary Information. We sincerely believe that the referee's suggestions and comments have greatly enhanced the clarity and rigour of our manuscript, and we are thankful for the opportunity to strengthen our work.

1. The number of independent InP QKD client chips employed in our experiments.

We thank the referee for pointing out the ambiguous statement in our original manuscript.

In the first submitted version: the TF QKD network was implemented with two InP QKD client chips and 10 different wavelength channels determined by the microcomb lines. Now this set of old data has been removed to Figure S8 and Table S6 in Supplementary Information.



In the revised version: the TF QKD network is now completely re-implemented using **20 independent TF-QKD transmitter chips** (see a new Fig.2c, where each PCB carries two InP chips to reduce packaging costs). These 20 InP chips are fabricated on a 3-inch wafer using foundry-level manufacture (see their fabrication in revised Supplementary Section 1, and see their characterisations in this letter and the significantly revised Fig.2) and they are now simultaneously deployed. The TF QKD network between 20 client chips is centralised with a microcomb laser, which provides all chip-level resources required for parallel and simultaneous 20-user QKDs in the network. All phase tracking and QKD data have been re-collected and reported in new Fig.3 and Fig.4. Phase tracking and QKD were implemented sequentially between each paired QKD client chips for each specific wavelength channel, with all other WDM channels leaving continuously running to emulate a parallel operation. We implement sequential measurement on these 20 independent TF-QKD chips through 10 WDM channels because of the limited resources such as RF electronic controls and synchronisations in our lab. We used commercial electronics (costs about \$70k per paired QKDs), and such electronic controls could be replaced by monolithic electronics and FPGAs in future to further reduce costs, which however is beyond the scope of our current laboratory demonstration.

In the revised **Abstract and Introduction**, we have rephrased the statement and unambiguously represents what we have achieved in this proof-of-principle demonstration of a chip-based TF-QKD network.

Quantum key distribution (QKD) leverages the principles of quantum mechanics to enable provably secure communication^{1,2}. One significant challenge persists in the development of large-scale QKD networks with a large number of clients over long communication-distances^{3,4}. While quantum relays continue to pose practical difficulties⁵, existing trusted node networks^{6–10}, point-to-multipoint networks^{11,12}, and wavelength-multiplexed entanglement networks^{13,14}, encounter issues such as reliance on trusted intermediaries or limited distances. Twin-field (TF)-QKD provides a compelling architecture that can overcome those issues while enhancing communication-distance¹⁵. Though long-distance point-to-point TF-QKD have been achieved^{16–22}, realising large-scale network requires scalable quantum devices. Here, we report proof-of-principle demonstration of integrated-photonic TF-QKD network with exceptional scalability and reliability. This network integrates twenty independent client-side QKD transmitter chips with a server-node-integrated optical microcomb chip. The microcomb generates a broad spectrum of ultra-low-noise coherent frequency combs with Hertz-level linewidths, which serve as seeds and references for all client chips. Each chip regenerates ultra-low-noise light phase-locked to microcombs and prepares quantum keys, achieving high performance, identical operation and high scalability through monolithic photonic integration. We sequentially implement pairwise QKD across twenty client chips through ten wavelength-multiplexed channels, with each surpassing the repeaterless bound at 370 kilometres in spooled fibre, achieving a networking capability (client-pairs $\times$ communication-distance) of 3,700 kilometres. Combining mass-manufacturability, cost-effectiveness and high scalability of integrated photonics with long-distance quantum communication represents a viable path to large-scale quantum networks.

works faces substantial technical challenges. These include development of many ultra-low-noise coherent laser sources, mass manufacture of identical, high-performance QKD chips that maintain uniformity across all client nodes, and system-level integration that enables scalable quantum node operation and quantum channel transmission, while remaining compatible with existing phase tracking. They collectively represent the fundamental requirements for TF-QKD network infrastructure, demanding simultaneous advances in photonic integration, manufacturing scalability, and system control.

Here, we present proof-of-principle laboratory demonstration of user-massively-scalable and long-haul TF-QKD network enabled by integrated photonics, named as “Weiming Quantum Chip-Network”. Our integrated-photonic QKD network comprises a central server chip that integrates an optical microresonator frequency comb (microcomb) on silicon nitride (Si_3N_4) platform, and 20 copies of independent client-side QKD transmitter chips that monolithically integrate all essential components for key preparation based on indium phosphide (InP) photonic circuits. These InP QKD client chips, fabricated on a 3-inch wafer, were characterised with identically high performance, reproducibility, and high operational yield, thus providing scalable quantum devices for network implementations. We harness integrated microcomb technology, which has revolutionized classical photonics^{24–26}, to dramatically enhance TF-QKD network's scalability and reliability by delivering a large number of ultra-low-noise, phase-coherent comb lasers for WDM-based networks across distributed client chips. We implemented the pairwise TF-QKD between 20 InP client chips through 10 wavelength-multiplexed channels aligned with microcomb lines, realising a total network spanning capability $NL/2 = 3700$ km (where $N=20$, $L=370$) without any trusted relays, after 10 trillion cycles of communication tested.

We also want to take this opportunity to explicitly explain the main distinction between the revised and original manuscripts, which mainly addresses the key concern raised by the referee: **whether a substantial number of InP QKD client chips were simultaneously deployed in this large-scale TF-QKD network?** Addressing this concern is indeed important, because it can answer a question: **whether integrated quantum photonic devices (including the microcomb server chip and QKD client chips), can indeed achieve the claimed scalability, when implemented with TF protocols and WDM architectures.**

To answer this question, we posit two pivotal aspects:

(1) The capability of generalised device architectures to accommodate diverse protocol requirements across multiple users (e.g., reconfigurability for WDM network implementations).

(2) The feasibility of mass-manufacturing integrated QKD transmitter chips with uniform performance through cost-efficient fabrication processes, while maintaining high-fidelity specifications for advanced QKD protocols. In the original version, we focused primarily on the (1) aspect. This was achieved by demonstrating the ultra-high coherent microcomb with a wide spectrum range at the server's side and employing 2 QKD chips configured with different wavelength settings sequentially (mimicking multi-user scenarios) to construct such a network.

However, we fully concur with the referee's insights regarding the pivotal challenge in such large-scale network applications: whether InP QKD client chips can provide high scalability through the fabrication and operation of multiple nearly identical chips. This directly corresponds to the (2) aspect. We fully agree with the referee that full characterisation of independent InP QKD chips (including fabrication, operation, and building blocks), is essential for demonstrating the practical scalability central to this work. Such systematic validation not only establishes the reproducibility of integrated quantum photonics, but also highlights essential advantages: miniaturisation, cost efficiency, and manufacturability — key enablers for future large-scale quantum networks. Following the referee's valuable suggestion, we have undertaken an extensive characterisation, packaging and testing of 20 copies of fabricated InP QKD transmitter chips to rigorously evaluate their yield, reproducibility, and scalability. This comprehensive study further validates the system-level operation of our TF-QKD network, which integrates 20 client chips with a centralised microcomb chip.

2. Full characterisations of 20 copies of InP QKD chips (fabrication, operation, and building blocks)

The 20 InP client chips used in our work were fabricated on a single 3-inch wafer. These chips were fabricated in the Smart Photonics Foundry in collaboration with colleagues in Eindhoven University of Technology. *As the referee suggested, in the revised manuscript, a brief introduction to the fabrication process of these InP client chips has been added in the Supplementary Section 1.*

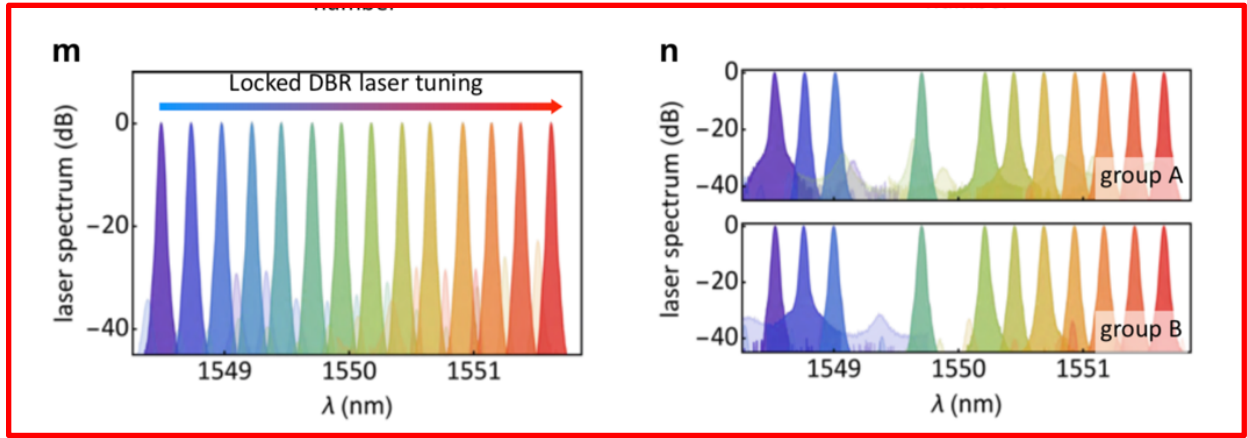
Integrated InP QKD client-chips: The quantum key distribution (QKD) transmitter client-chips were monolithically fabricated on a 3-inch indium phosphide (InP) photonic integration platform, including all functional components for QKD such as distributed Bragg reflector (DBR) lasers, intensity modulators (IMs), phase modulators (PMs), attenuators, and photodiodes (for calibration). The *n*-doped substrate serves as a common ground contact across the entire wafer. Device fabrication began with metalorganic vapour phase epitaxy (MOVPE) to grow different active and passive regions or structures, followed by a series of precision etching processes to define the various photonic waveguide components. The active regions incorporated multiple InGaAsP quantum well layers sandwiched between quaternary InGaAsP barrier layers, with semiconductor optical amplifiers (SOAs) formed by selectively etching the active layers to create gain sections. Passive waveguide regions were realised using low-doped InGaAsP layers with a 1.25 μm bandwidth, optimised for minimal absorption in the telecommunications C-band. The upper cladding consisted of sequentially deposited p-doped InP and InGaAs layers. Electrical isolation between components was achieved through controlled etching of the top cladding layers, which separated the active regions and reverse-biased passive sections. Following passivation and planarisation using polyimide organic polymer, the final processing steps involved depositing top metal contacts and patterning coplanar waveguide transmission lines to establish electrical interconnects and signal routing across the chip.

2.1 Full characterisations of 20 independent QKD lasers + references lasers on 20 separated InP chips:

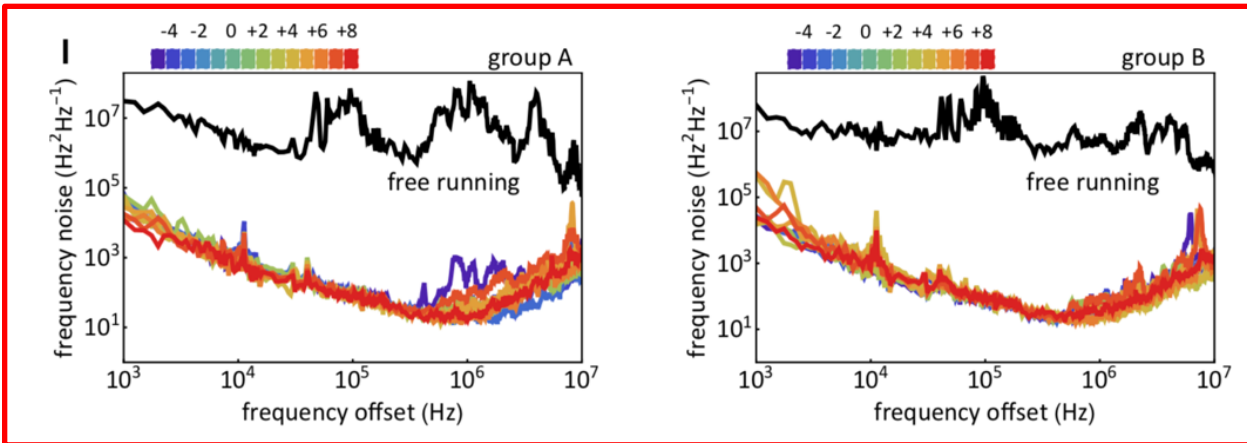
For the InP lasers, we demonstrated two key functionalities: (i) wavelength tunability of lasers across the entire spectral range of the network, and (ii) injection-locked spectra and frequency noise, across 20 separated InP chips, with all performance satisfying the protocol requirements. We didn't show the characterisation of lasers' initial spectra as the lasing exhibits multi-parametric dependencies, including configurations of distributed

Bragg reflector (DBR) and voltage/current in semiconductor optical amplifier (SOA), and thermal tuning. This inherent variability precludes the establishment of universal initial characterization metrics across all devices. We show the significant reduction of frequency noises before and after injection-locking operation across 20 separated InP chips. We also employed the wavelength tuning capability and spectral/linewidth characteristics after injection-locking operation, which directly reflect their functional reliability in actual operating conditions.

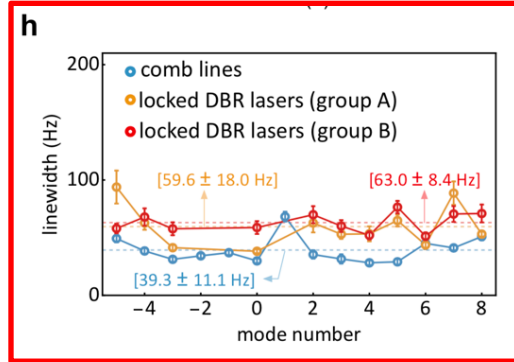
In a new Fig.2m, we have now added the measured optical spectra of a single laser continually tuning to the microcomb lines, and in a new Fig.2n, we have now added the measured optical spectra of 20 independent QKD lasers (10 lasers in group A and 10 lasers in group B in the network) on 20 separated InP chips and additional reference lasers (10 lasers in total, we show 2 lasers as examples in Fig.2n), where those independent lasers on separated chips have been locked to the central microcomb's lines to regenerate the quantum signals and reference signal.



In a new Fig.2l, we have now reported the measured laser frequency noises when they are free running and injection-locked, for those 20 independent QKD lasers (10 lasers in group A + 10 lasers in group B) on 20 separated InP chips and 2 additional reference lasers.



In a new Fig.2h, we have reported the measured laser linewidth when they are injection-locked, for those 20 independent QKD lasers (10 lasers in group A + 10 lasers in group B) on 20 separated InP chips and 2 additional reference lasers. Those data for microcomb are now also combined in the new Fig.2g.



Details of laser characterisations have been added in the revised main text.

for pulsation and key encoding, as illustrated in Fig.2a. We characterise the regeneration of ultra-low-noise light in those wavelength-tunable slave lasers across 20 InP chips. After locking the DBR lasers to the comb lines, we re-characterised frequency noises, as shown in Fig.2l. Figure 2h summarises measured linewidths for comb lines and locked local lasers, demonstrating substantial frequency noise suppression that achieves intrinsic linewidths of around 60 Hz for TF-QKD. As shown in Fig.2m, a client-chip locked DBR laser achieve 3.2 nm continuous wavelength tuning, spanning the λ_{-5} to λ_{+8} range. All DBR lasers across the 20 chips demonstrate independent wavelength tunability and injection locking to comb lines, with each achieving > 30 dB side-mode suppression (Fig.2n). These results demonstrate the capability of massive integration and operation of low-noise lasers for scalable WDM-based TF-QKD networks.

Details of laser characterisations have been added in the Fig.2 caption.

zero V_{π} or visibility indicate 3 hardware failure of modulators, resulting in a 97.5% yield. (l), Frequency noise characterisation of phase-locked slave lasers on the QKD client-chips, showing comparable performance to the microcomb (see summary in (h)). In (g) and (i), free-running lasers (black) are plot for comparison. (m), Continuous tuning spectrum of a single client-laser, aligning and phase-locking to specific comb lines. (n), Spectra of injection-locked slave lasers on different client-chips. Error bars denote the ± 1 standard deviation of measured data.

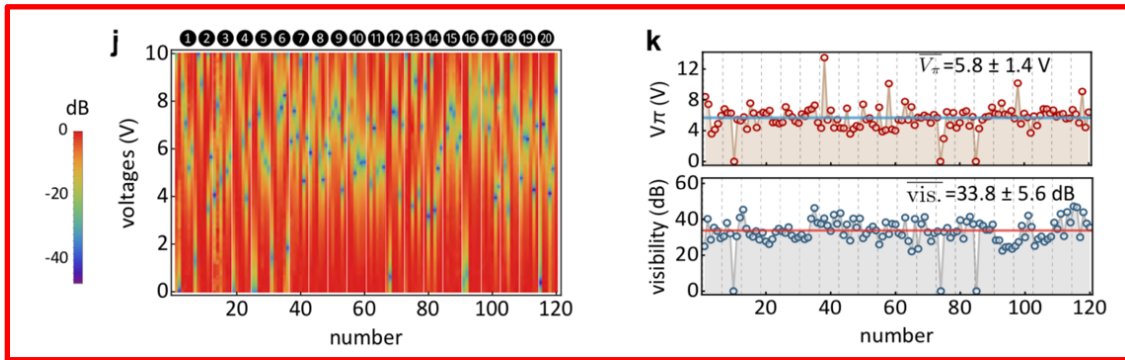
In the Supplementary Information Section 4, we have added details of microcomb generation.

Dark-pulse microcomb generation at the server chip: The Si_3N_4 microresonator and integrated distributed feedback (DFB) laser were mounted on the thermoelectric coolers, respectively with 1 mK temperature control accuracy. The DFB laser chip was controlled by a six-axis stage to precisely adjust the coupling angle and air gap between chips. Under the condition of small detuning between the laser and

microresonator's mode, we implemented 1 kHz sawtooth-wave current scanning of the DFB laser while performing synchronous coupling air gap adjustments to identify the optimal dark-pulse frequency comb generation regime. This procedure enabled the determination of the optimised laser current and coupling air gap parameters, allowing subsequent turnkey acquisition of the microcomb outputs through direct loading of predetermined current values to the DFB laser under invariant experimental conditions. An optical isolator was inserted at the output of the microcomb to prevent reflected noise light from disturbing the locking condition. Then, part of the microcomb was fed into the photodiode, optical spectrum analyser and phase noise analyser for monitoring and performance characterisation. The desired comb lines ranging from λ_{-5} to λ_{-3} and λ_{+2} to λ_{+8} were selected and intensity equalized with a waveshaper. An Erbium-doped fibre amplifier was used to ensure that the comb had an intensity of at least -20 dBm on-chip power when injected as seed lights onto the QKD transmitter chips. The spacing between different wavelength channels was 30.03 GHz (equal to the FSR of the microresonator), misaligning with the standard ITU channel spacing. Integrated microcombs matching standard ITU channel spacing (e.g., 50/100 GHz) can be readily implemented⁷⁴, enabling full utilisation of mature WDM components for wavelength allocation and spectral filtering. This could facilitate cost-effective deployment in real-field quantum communication networks. After the comb line assignment based on network configuration, polarisation controllers were used to align the polarisation of the seed lights with the optical mode on client chips.

2.2 Full characterisations of 120 independent modulators on 20 separated InP chips:

As the referee highlighted and suggested, for QKD protocols based on weak coherent states, the key parameters of modulators are the V_π of phase modulators and modulation visibility (i.e., extinction ratio, ER) of intensity modulators, because these parameters fundamentally determine the driving efficiency and bit error rate (BER) of the QKD system. We have now implemented full characterisations of 120 independent PMs and IMs on 20 separated InP chips, and results are reported in new Fig.2j, Fig.2k and Fig.2i. We therefore demonstrate high yield modulators with a V_π of 5.8 ± 1.4 V and a high modulation visibility of 33.8 ± 5.6 dB. All EO modulators functioned as designed under normal operation, while 3 out of 120 modulators showed failures due to fabrication imperfections, yielding a high yield rate of 97.5%. Fortunately, we could implement a single-drive configuration using one of the EOPMs in each IM, instead of a push-pull dual-drive configuration using two EOPMs in each IM, ensuring fully operational QKD networks using 20 independent InP chips.



In the revised main text Page 4, we have added a paragraph to describe the details of InP chip characterisations.

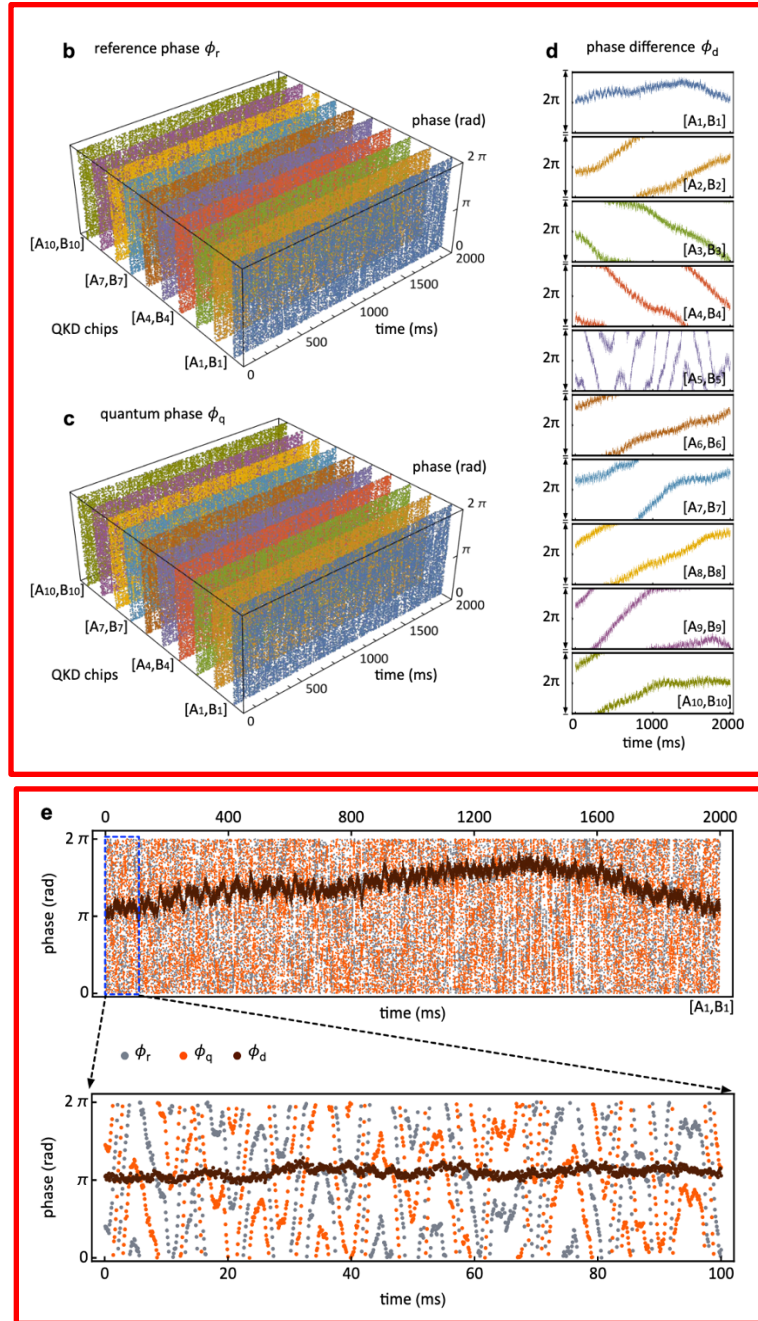
The phase modulation was achieved using a single-arm electro-optic PM (EOPM), while intensity modulation was implemented using Mach-Zehnder modulators (MZMs) with dual PM arms (1.25 mm length, 25 GHz bandwidth) for loss balance and high extinction ratio. Figure 2j reports measured modulation curves for all EOPMs in IMs. It reveals 117 of 120 EOPMs (97.5% yield) functioning as designed across all 20 chips, with three hardware failures. These modulators exhibited consistent performance, as shown in Fig. 2k, with an average V_π of 5.8 ± 1.4 V and interference visibility of 33.8 ± 5.6 dB.

In the Supplementary Information Section 4, we have added details of quantum keys encoding at the InP client chips.

Quantum keys encoding at the InP client chips: Laser diode controllers were used to control the SOA section of on-chip DBR lasers and the chip's temperature, and the DBRs were controlled with additional voltage sources. The frequency detuning with the microcomb seed light could be carefully controlled to achieve injection locking conditions. The detuning range was initially determined by synchronously adjusting above operating parameters to make robust injection-locking operation. Subsequently, with all parameters (including seed light power) maintained constant, stable locking states can be reliably achieved during each experimental run through rapid SOA current scanning until reaching predetermined values. Such procedures allow for individual calibration of the lasers across all 20 client chips. The DBR lasers were running in continuous mode. For pulsation, electrical signals from high-speed arbitrary waveform generators (AWGs) were amplified and mixed with DC bias signals, and then fed into the IMs III. Additional AWGs were used to generate the electrical control signals for the PM I and IM I, II according to the sequence shown in Fig. 3a to finish the phase randomisation and coding, and decoy state preparation and attenuation. Experimental characterisations of optical injection locking of local DBR lasers and modulators are provided in Fig. 2 of the main text. Figures 2j and 2k demonstrate the high yield of our electro-optic modulators, with 97.5% (117 of 120) functioning as designed under normal operating conditions, while 3 devices exhibited failures due to fabrication imperfections. The device's design allows for flexible configuration. We successfully implemented a single-drive scheme using one electro-optic PM (EOPM) per IM as an alternative to the dual-drive push-pull configuration (which would require two EOPMs per IM). This adaptability ensured full operational capability across all 20 independent InP chips in the QKD network.

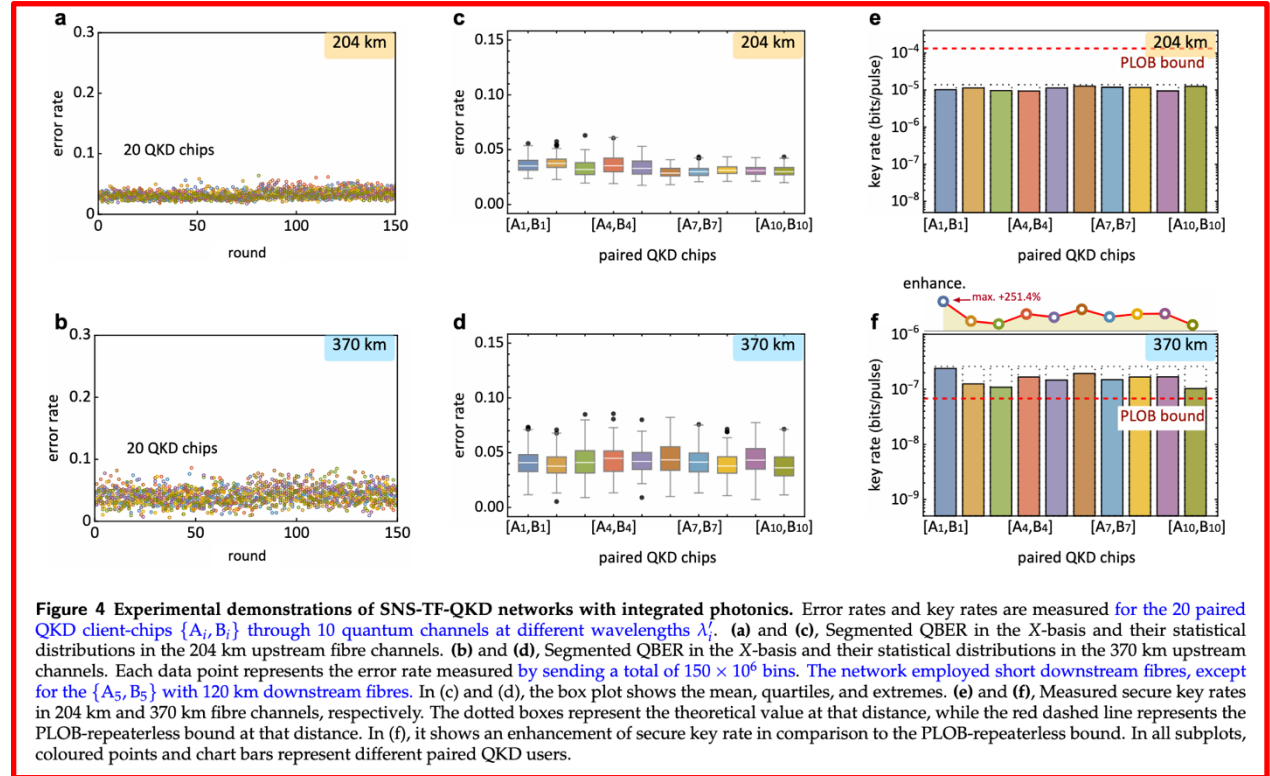
3. Demonstration of TF-QKD network with 20 InP client-chips and a microcomb chip

We have reimplemented the entire TF-QKD network using **20 TF-QKD chips**. Phase tracking between those 10 pairwise client-chips $\{A_i, B_i\}$ is reported in the updated Fig.3.

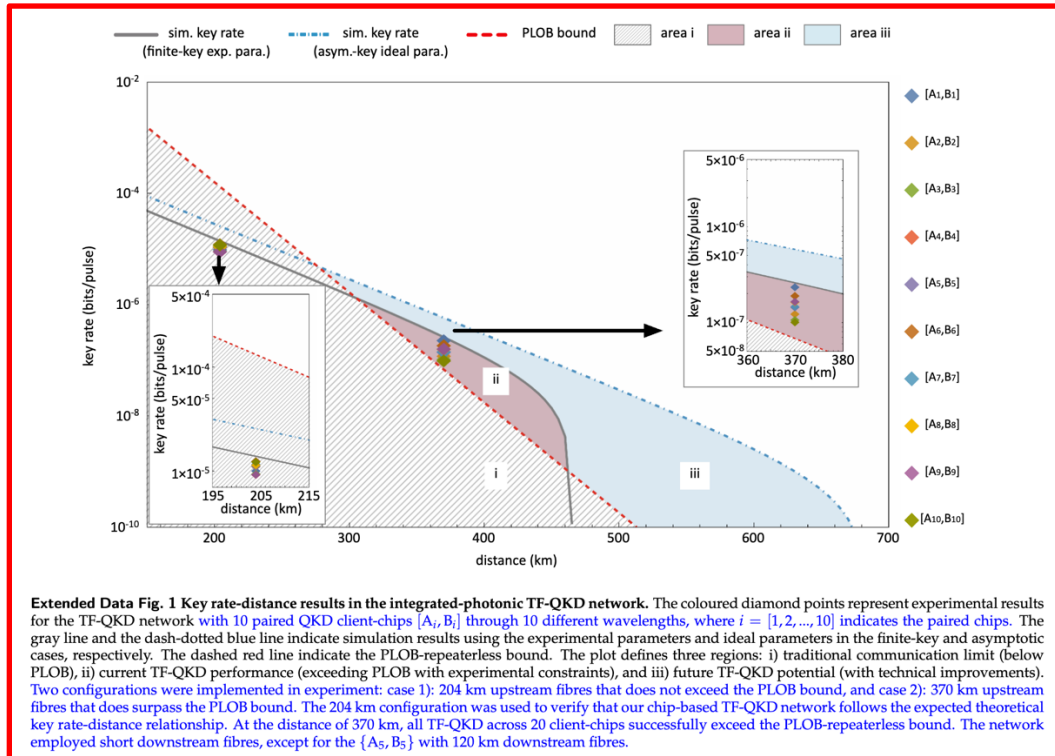


NEW PHASE TRACKING RESULTS: Fig.3... (b) and (c). Experimental characterisation of phases across the fibre links between those 10 pairwise client-chips $\{A_i, B_i\}$ and the server chip: (b), phases for the reference signals (Φ_r) at the wavelength of λ_0 , (c), phases for the quantum signals (Φ_q) at the wavelength of λ'_i , and (d), their relative phase differences $\Phi_d = \Phi_r - \Phi_q$ (e). An example of phase distributions for the $\{A1, B1\}$ paired QKD chips. Inset: zoom-in view of the initial 100 ms window.

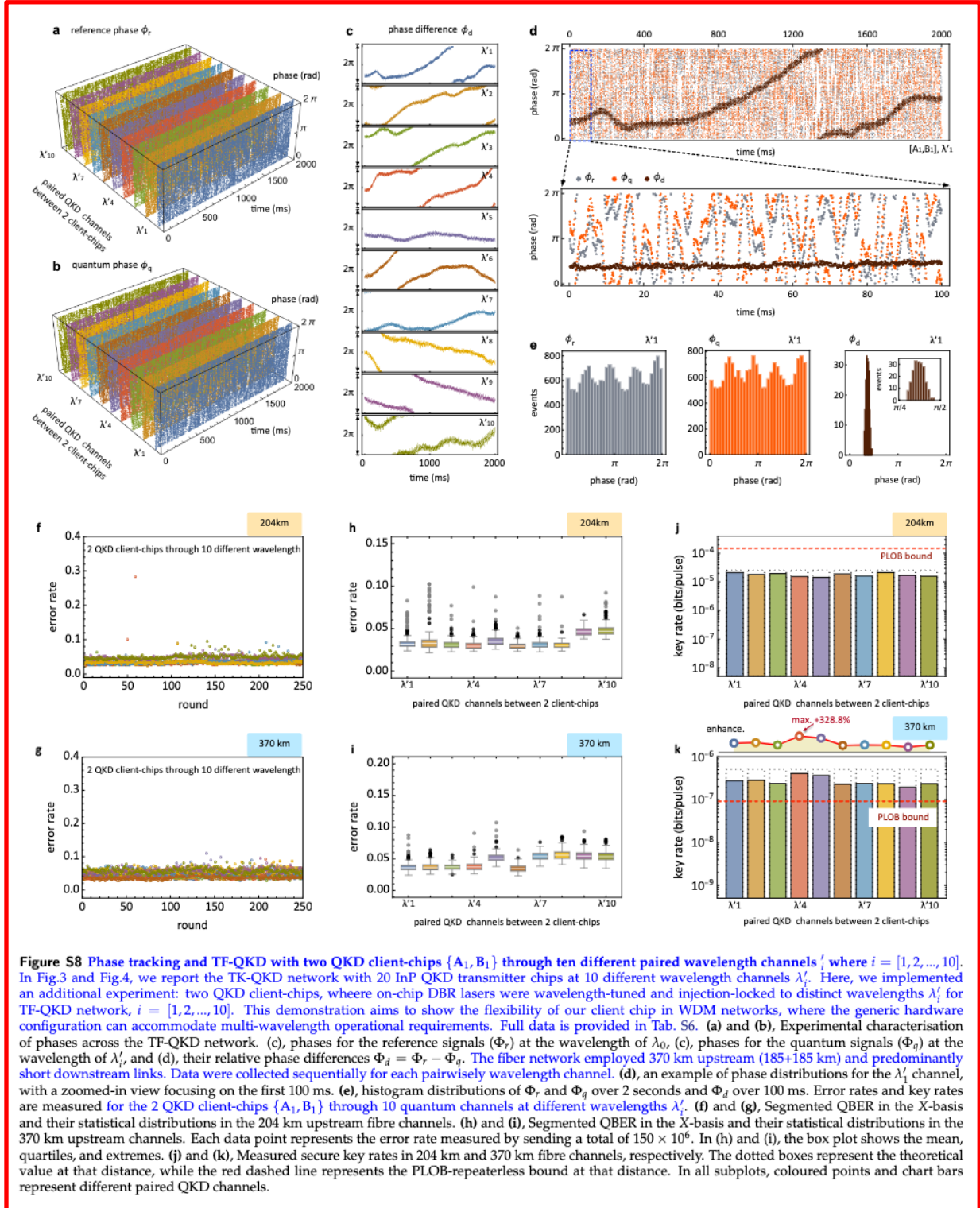
NEW QKD RESULTS: Error rates and key rates for the 10 pairwise client-chips $\{A_i, B_i\}$, in total 20 chips, are reported in the new Fig.4.



Extended Data Fig.1, along with additional supporting data is provided in the Supplementary Information.



OLD PHASE TRACKING and QKD RESULTS: The experimental data of previous TF QKD network with only 2 InP transmitter chips operating at different wavelength has been moved to [Supplementary Information Fig.S8](#).



Full experimental data for 20 QKD client chips linked via 10 different wavelengths (new data), and 2 QKD client chips linked via 10 different wavelengths (old data), have been provided in Table S5 and S6, respectively.

Throughout the revised manuscript, we clarified that this work was accomplished in the lab with 20 independent QKD chips through 10 WDM channels and all QKD data were obtained sequentially for each paired chips at a wavelength channel. In the revised **Abstract, Introduction, and the caption of new Fig.2, Fig.3 and Fig.4**, we have clarified the implementation of 20 QKD client-chips in the TF-QKD network. The following are some main modifications in the revised main text. Supplementary Information has also been revised accordingly.

In the revised main text, Page 2, we have added a sentence: *"20 copies of InP QKD chips synergistically leveraged in this work are shown in Fig. 1c."*

In the revised main text, Page 4, we have rephrased a sentence as: *"Twenty InP chips (footprint $4.6 \times 2 \text{ mm}^2$ each, see Fig.2i) are divided to group A and group B, to implement pairwise TF-QKD between the two chips $\{A_i, B_i\}$, where $i = [1, 2, \dots, 10]$ represents paired-users sharing identical wavelengths λ_i . λ_i are aligned with microcomb lines, remapping from $\lambda-5$ to $\lambda-3$ and $\lambda+2$ to $\lambda+8$."*

In the revised main text, Page 6, we have rephrased a sentence as: *"We implemented lab-scale proof-of-principle quantum network of 20 QKD client-chips linked via 10 WDM channels. Phase tracking and key distribution were sequentially executed between paired chips $\{A_i, B_i\}$ due to resource constraints in electronic controls and clock synchronisation. All 10 WDM channels maintained parallel fibre transmission interconnecting 20 QKD chips during sequential QKD operation, with non-target channels at high power to estimate an upper bound for crosstalk and noise (emulating realistic scenarios)."*

In the revised main text, Page 6, we have rephrased a sentence as: *"The QKD network contains $N = 20$ client chips (that is, 10 paired chips connected via 10 WDM channels), achieving a total networking capability of $NL/2 = 3700 \text{ km}$."*

In the revised main text, Page 7, we have rephrased a sentence as: *"Secure quantum keys were then distributed across the network between 20 QKD client-chips..."*

In the Fig.2 caption, we have now rephrased: *"Paired client-chips of $\{A_i, B_i\}$ send quantum states through the λ_i -channel in long-haul upstream fibres (where all wavelength channels are multiplexed), with single-photon interference measurements at the server node returning secure keys."*

In the Fig.4 caption, we have now rephrased: *"Error rates and key rates are measured for the 20 paired QKD client-chips $\{A_i, B_i\}$ through 10 quantum channels at different wavelengths λ_i ."*

In the revised Conclusion, we have rephrased a sentence: *"In summary, we have implemented a proof-of-principle integrated-photonic QKD network, demonstrating high scalability and reliability. Through the validation of bit transmission, the architecture and hardware have been proven capable of supporting many-user networks accommodating 20 client-chips, spanning a total networking capability exceeding 3700 km, with each channel enabling the distribution of secure keys that surpass the repeaterless bound."*

We have rephrased the Extended Data Fig.2 (Fig.5 in the initial submitted version).

Extended Data Fig. 2 Summary of state-of-the-art QKD and QKD networks without trusted intermediate nodes. The size of points in the visualisation represents the total quantum networking capability of $NL/2$, where N denotes the number of QKD users and L signifies the channel distance. In the TF-QKD network presented in this work, we achieved a total quantum networking capability of $NL/2 = 3700 \text{ km}$, with $N = 20$ chip-based QKD users and $L = 370 \text{ km}$ channel distance. Some notable demonstrations of QKD and QKD networks include: the longest satellite-based QKD in ref.[63]; the longest fibre-based TF-QKD in ref.[20]; deployed TF-QKD in ref.[22]; the longest MDI-QKD in ref.[64]; longest chip-based MDI QKD in ref.[41]; a three-user MDI-QKD network in ref.[65]. Results from QKD networks relying on trusted intermediate nodes are excluded from this summary.

Throughout the Supplementary Information, we have now clarified the implementation of 20 QKD client-chips in the current TF-QKD network.

We appreciate the referee's insightful comment regarding the role of microcomb lasers and TF-QKD chips in the TF-QKD network. We have now emphasised a critical advancement: the scalability of InP-based QKD chips, which we have now demonstrated in the revised manuscript. To ensure experimental results are presented with roughly equal rigour, and following the Editor's suggestion to streamline the title, we have revised it to: "Large-scale Quantum Communication Networks with Integrated Photonics" (replacing the initial submitted version: "Scaling Quantum Communication Networks with Microcomb-Driven Integrated Photonics").

In summary, these full characterisations of 20 copies of InP QKD chips have verified the high yield and reproducibility of all lasers and modulators on these InP chips, demonstrating their strong scalability for large-scale implementation of QKD networks with integrated QKD transmitters and microcomb lasers.

Given these verified highly identical InP client chips, we have now recollected every data point in Fig.3 and Fig.4 to demonstrate the microcomb-driven 20 InP client chips-based TF QKD system. We once again express our gratitude to the referee for the profound and visionary insights. We are confident that the current version has been substantially improved, with the results representing an important step toward the application of integrated photonic technologies to quantum communication networks.

• *Are the RF signals prepared from the AWG for the encoding in the QKD transmitters random sequences or fixed repeated sequences? If the latter, what is the length of the sequence?*

In this proof-of-principle demonstration, the RF signals were preset to comply with the protocol requirements. Quantum states were sequentially encoded in either the Z or X basis, with a total of 10^{12} rounds transmitted for each paired user's verification to account for finite-size effects. Repeated sequences were used and cycled until sufficient tests were completed based on the basis choice probabilities (experimental bits sent have been reported in Tab. S5). While our current implementation relies on predefined sequences, the high bandwidth of InP modulators could support real-time random encoding sequences for practical field deployments—though this lies beyond the scope of our present work. **In the revised manuscript, we have now added details:**

obtained in the X-basis. Our proof-of-concept implementation employed sequential transmission of encoded bins in repeated cycles to characterize both network gain and quantum bit error rate (QBER). Figures 4a-d report the measured QBER_X in the phase-sensitive X-basis for the SNS-TF-QKD over 204 km and 370 km distances, with data collected across all 20 client-chips. Experimental results show QBER_X values of 2.87-3.63% for 204 km and 3.50-4.17% for 370 km. Full experimental data across all 20 client-chips, including gain and Z / X-basis QBER, are summarised in Tab. S5. The low QBER results

• *Is the post-processing part of the protocol performed in real-time or offline after the quantum phase ended?*
 • *If the post-processing is performed offline and the signals from the AWG are made of repeated sequences, I suggest referring to the experiment as a proof-of-principle QKD experiment in the main text.*

The post-selection of phase windows was performed offline during the data sifting procedure.

As the referee rightly suggested, we have explicitly clarified and characterised this work as a "proof-of-principle demonstration" of TF-QKD network, with clarifications added throughout the revised manuscript, in particular in Abstract, Introduction, and Discussion.

Some additional minor points:

- In the section "Demonstration of microcomb-driven integrated TF-QKD network," the authors write: "The infinite-size effect has been taken into account by sending a total of 10^{12} bins in each case. Moreover, we obtained the secure key rates at the two different communica..." I guess "infinite" is a typo for "finite."

We thank the referee for their meticulous review. The typo has now been corrected, and we have performed careful checks throughout the revised manuscript to ensure accuracy.

- In equation S17, I suggest having the symbol f_{EC} in the formula for the error correction efficiency and keeping the value of 1.1 described in the text.

Following the referee's suggestion, we have updated Equation (S17) to explicitly include the symbol f_{EC} while maintaining the value of 1.1 as described in the text.

In conclusion, based on my previous comments, I currently cannot recommend the publication of the manuscript in Nature.

We believe all of the referee's concerns have been thoroughly addressed both in this response letter and in the revised manuscript. We are deeply grateful for the referee's insightful and constructive comments, which have been very instrumental in helping us significantly improve our work. The thoughtful feedback has significantly strengthened both the technical rigour and clarity of our manuscript.

Referee #1 (Remarks to the Author):

Please find below the review of the revised Nature Manuscript ID: 2024-10-21482 entitled "Large-scale Quantum Communication Networks with Integrated Photonics", by Professor Wang and co-authors. I have carefully read and considered the author's detailed and comprehensive response to the comment raised by all reviewers. I am pleased to read that in their response and revised manuscript, the authors report a profound improvement of the original experiment.

Specifically, the first manuscript featured an ambiguity regarding the actual scale of the experiment. While it was suggested that the TF QKD experiment was performed using 10 independent pairs of client chips in parallel, there were a few indications that only 2 client chips were used and therefore several claims related to scalability and massive parallelism could not be justified.

The authors acknowledge that "In the first submitted version: the TF QKD network was implemented with two InP QKD client chips and 10 different wavelength channels determined by the microcomb lines."

Therefore, they propose a new experiment:

"In the revised version: the TF QKD network is now completely reimplemented using 20 independent TFQKD transmitter chips (...) and they are now simultaneously deployed. The TF QKD network between 20 client chips is centralised with a microcomb laser, which provides all chip-level resources required for parallel and simultaneous 20-user QKDs in the network."

The new experiment convincingly demonstrates the scalability claimed originally. The authors provide comprehensive and extensive characterization measurements of 20 InP client chips, which demonstrate high level of reproducibility and consistent high performance across all devices, reaching ultra-low linewidths under optical injection locking from a microcomb device and achieving TF-QKD secure key rate above the PLOB bound over 10 independent links.

Parallelism could not be fully demonstrated due to resource limitation. The authors explain that it is nevertheless emulated by measuring TF-QKD on client pairs sequentially while keeping the other links continuously active, which is acceptable for a proof-of-principle.

The revised manuscript is a substantial improvement of the experiment scale, and I acknowledge the authors' efforts and time in addressing all comments made during the first review. The high-quality cross-disciplinary results are expected to impact a broad readership from diverse background. I'm inclined to recommend publication of this work, however, this is pending carefully addressing the comments below, which I hope will help enhancing the accessibility to the general reader, lifting all risks of experimental misinterpretation, and meeting the expectations of the expert reader.

We sincerely thank the Referee for their extremely valuable comments and suggestions, which have been instrumental in refining and improving our work. We are grateful for their recognition of the newly implemented experiments and revisions in the first resubmitted manuscript, which have clarified the true scale of the experiments and demonstrated the network's scalability, as suggested by the Referee in the first review process. We appreciate the reviewers' insightful comments and suggestions on scalability, security, and experimental details, pointed out in the second review. In the revised manuscript, we have added new experimental data and provided further clarifications to support our claims. The manuscript has been revised to better balance the broad accessibility and specialist rigor. In particular, the Abstract and Introduction have been rephrased to emphasise the scalability and cross-disciplinary relevance of our work for a broad readership. We believe that all the referee concerns have been fully addressed, and their constructive feedback has significantly enhanced the overall quality of the manuscript.

Reviewer Comment 1, Readability:

the revised manuscript is very technical in its present form and may not directly be suitable for a general readership. There is indeed a challenge in finding the right balance between describing the extensive characterization dataset, describing the TF-QKD experimental conditions and performance, and a discussing the relevance and perspectives of this work for a practical, real-field implementation of TF-QKD networks. A suggestion would be that the authors consider focusing more on the latter than the former by moving some of the characterization measurements to the extended data section (or supplementary information) and including more of the discussion on the feasibility of a practical TF-QKD WDM network in the main text. In my opinion, this would make the manuscript more accessible to a broad readership, while still satisfying the experts expectations:

Author Reply 1: We are grateful to the Referee for their valuable suggestions on improving the readability of our manuscript. In the revised version, we have carefully balanced broad accessibility with specialist rigor. As the Referee suggested, we have now moved some characterisation details to the Supplementary Information, such as the descriptions of SNS-TF-QKD experimental flowchart. We have kept those necessary device characterisation data in the main text to provide readers with an immediate and objective impression of the performance of integrated quantum photonic chips, and to show the current level of technological advancement for both general and expert audiences. Additionally, following the Referee's suggestion, we have also revised the Abstract and Introduction to better highlight the scalability and cross-disciplinary relevance of our work; In the Conclusion, we have further strengthened the discussion on scalability, security and the feasibility of a practical TF-QKD network, while providing references to the Supplementary Information for a more detailed discussion. See Box 1.

Box 1: rephrased abstract

Quantum key distribution (QKD) leverages the principles of quantum mechanics to enable provably secure communication^{1,2}. One significant challenge persists in the development of large-scale QKD networks with a large number of clients over long communication-distances^{3,4}. While quantum relays continue to pose practical difficulties⁵, existing trusted node networks^{6–10}, point-to-multipoint networks^{11,12}, and wavelength-multiplexed entanglement networks^{13,14}, encounter issues such as reliance on trusted intermediaries or limited distances. Twin-field (TF)-QKD provides a compelling architecture that can overcome those issues while enhancing communication-distance¹⁵. Though long-distance point-to-point TF-QKD have been achieved^{16–22}, realising large-scale network requires scalable quantum devices. Here, we report proof-of-principle demonstration of an integrated-photonic TF-QKD network with exceptional scalability and reliability. This network includes twenty independent client-side QKD transmitter chips with one server-side optical microcomb chip. The microcomb generates a broad spectrum of ultra-low-noise coherent frequency combs with Hertz-level linewidths, which serve as seeds and references for all client-chips. Each client-chip regenerates ultra-low-noise light phase-locked to microcombs and prepares quantum keys through monolithic integration of all components. We sequentially implement pairwise QKD across twenty client-chips through ten wavelength-multiplexed channels, with each surpassing the repeaterless bound at 370 kilometres in spooled fibre, achieving a networking capability (client-pairs $\times$ communication-distance) of 3,700 kilometres. **We further demonstrate the wafer-scale reproducibility of both server-side microcomb chips and client-side QKD transmitter chips, together establishing the system-level scalability.** Combining mass-manufacturability, cost-effectiveness and high scalability of integrated photonics with long-distance quantum communication represents a viable path to large-scale quantum networks.

rephrased introduction

Here, we present proof-of-principle laboratory demonstration of user-massively-scalable and long-haul TF-QKD network enabled by integrated photonics, named as “*Weiming Quantum Chip-Network*”. Our integrated-photonic QKD network comprises a central server chip that integrates an optical microresonator frequency comb (microcomb) on silicon nitride (Si₃N₄) platform, and 20 copies of independent client-side QKD transmitter chips that monolithically integrate all essential components for key preparation based on indium phosphide (InP) photonic circuits. **These client-side QKD chips fabricated on a 3-inch InP wafer and server-side microcomb chips fabri-**

cated on a 4-inch Si₃N₄ wafer both demonstrated high performance, reproducibility, and operational yield, thus providing scalable quantum devices for network implementations. We harness integrated

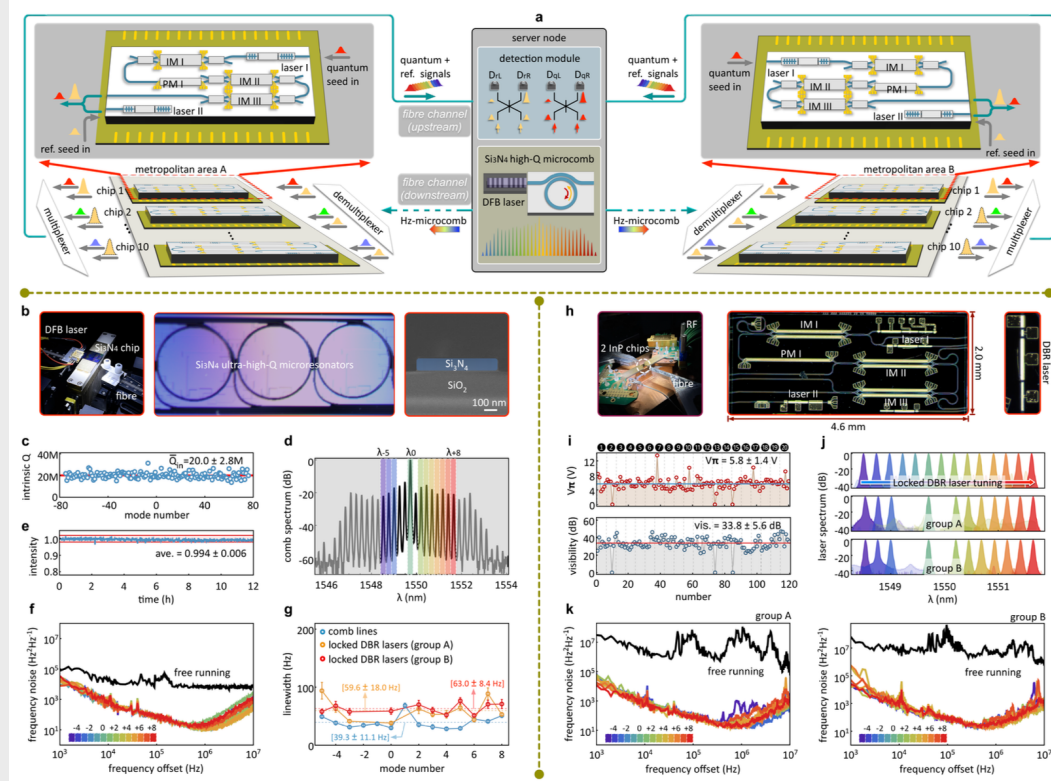
Box 1: rephrased conclusion**Discussion and conclusion**

In summary, we have implemented a proof-of-principle integrated-photonic QKD network, demonstrating high scalability and reliability. Through the validation of bit transmission, the architecture and hardware have been proven capable of supporting many-user networks accommodating 20 client-chips, spanning a total networking capability exceeding 3,700 km, with each channel enabling the distribution of secure keys that surpass the repeaterless bound. Integrated photonic quantum devices and systems offer several key features that can bolster the construction of practical QKD networks. Firstly, the system supports a large number of QKD users, facilitated by massively manufacturable and scalable transmitter chips that combine full integration, high performance, and cost-effectiveness to enable service accessibility, and microcomb-driven WDM protocols that ensure massive parallelism across the network. Secondly, the communication distances are extended by leveraging ultra-low-noise microcombs and lasers for advanced QKD protocol execution, [with prospects for further improvements](#)²⁰. Thirdly, network security is enhanced through the implementation of SNS-TF-QKD, maintaining MDI properties for heightened security compared to trusted node networks. [While certain aspects under the current experimental conditions, such as imperfect phase randomisation and potential vulnerabilities in the injection-locking technique, require further improvement to address possible loopholes \(see Supplementary Section 6\), these limitations do not affect the core demonstration of scalability and reliability of the quantum networking chips.](#) Finally, in future, our integrated quantum photonic devices and technologies could be extended to field-deployable QKD networks [with different practical configurations. These include implementing asymmetric networks by further reducing low-frequency noise in the microcomb lasers, and establishing fully-connected or reconfigurable networks by combining server-side quantum frequency conversion \(see Supplementary Section 5\) with the demonstrated client-side wavelength tunability \(see results in Fig.S11 and Table S6\).](#)

The spectrum of integrated optical microcombs can be substantially broadened through more dedicated engineering^{54,55}, and in conjunction with broadband tunable integrated lasers⁵⁶, it's promising for the network to accommodate hundreds of manufacturable QKD client chips. Through incorporating lower dark count SNSPDs and optimised protocols⁵³, it becomes feasible to extend individual quantum communication links to a 1000-kilometre distance²⁰. An integrated-photonic quantum networking system is anticipated to

a. Fig. 2 could be split or be made more compact. Fig 2d and e are redundant. Fig 2j is not easy to appreciate, a plot of the max extinction ratio per IM would be quicker to understand. 2j and 2k could be moved to a SI section.

Author Reply 1(a): We have reorganised Figure 2 following the Referee's suggestions. Specifically, we have moved the original Fig. 2e to the Supplementary Fig.S4e to highlight the time-stability of the entire microcomb system. The original Fig.2d, which shows the spectral distribution of the microcomb and illustrates both the comb laser bandwidth and wavelength labels used for paired TF-QKD, has been retained as [Fig. 2d](#). The original Fig. 2j has been removed entirely. The maximum extinction ratio per IM—defined as visibility—was previously provided in Fig. 2k. This panel, now revised and included as [Fig. 2i](#) in the revised manuscript, shows the performance and yield of the 120 EOPMs, which is essential for supporting our claims on the scalability of integrated-photonic networks. We believe Fig.2 is now more focused and clearer, as the referee suggested. [See Box 2.](#)

Box 2: modified Fig.2:**modification in Fig.2 caption:**

indicate 3 hardware failures of modulators. (j), Locked DBR lasers' spectra on QKD-client chips. The upper show continuous tuning spectrum of a single client-laser, aligning and phase-locking to specific comb lines. The mid and below show spectra of injection-locked slave lasers on different client-chips. (k),

b. Statements such as “While this is currently a lab-scale demonstration, our integrated quantum photonic devices and technologies can be readily extended to field-deployable QKD networks” should be supported in the main text, as they immediately raise questions on stabilization and security. Therefore, the discussions of SI Section 5 (Towards real-field implementation of integrated-photonic TF-QKD networks – in particular considerations on channel asymmetry) and Section 6 (Security analysis – in particular security of OIL for TF-QKD) should if possible be summarized in the main text.

Author Reply 1(b): Following the Referee’s suggestions, in the Conclusion section, we have further strengthened the discussions on the scalability, security and the feasibility of a practical TF-QKD network, and have also rephrased this sentence in Conclusion to avoid any misleading (see Box 1). We have also provided references to the Supplementary Information for detailed discussions.

Reviewer Comment 2, Packaging:

a. Each package features 2 chips with optical I/O on both sides, which might be challenging to manage. Out of curiosity, how many fibres are used per chip and is packaging done using fibre arrays or individual fibres? Do the authors have an estimation of the fibre coupling losses?

b. Are both chips of the same client pair assembled on the same package or are both clients of the same pair on physically separated nodes?

Author Reply 2 (a,b): We appreciate the referee's comments regarding the insufficient description of chip packaging and experimental testing configurations. As shown in Fig. 1c and Fig. 2h, the

client-side InP chips were electrically packaged on a PCB (two chips per board) to ensure stable loading of multi-channel RF signals. For flexible optical characterisation, the chips were coupled via optical fibres mounted on translation stages. As illustrated in Fig. 2a and implemented in Fig. 2h, each InP chip was accessed using three single-mode fibres: one for reference seed (signal) input/output, and two for quantum seed (signal) input/output. The coupling loss between each InP chip and fibre I/O was estimated to be around 4 dB. For future large-scale deployment, fibre-array packaging can be adopted to enhance operational stability and user accessibility.

The two InP chips of the same client pair were always tested on physically separated nodes.

In response to the Referee's suggestion, we have included additional descriptions of the packaging and testing procedures in the **Supplementary Information Section 4.1 (see Box 3)**.

Box 3: new text in Supplementary Information Section 4.1:

Quantum keys encoding at the InP client chips: The InP client chips were electrically packaged on a PCB (two chips per board) to ensure stable loading of multi-channel RF signals. We mark that in the TF networking implementation, the two InP chips of the same client pair were always tested on physically separated nodes. The InP chips were coupled via optical fibres mounted on translation stages. As illustrated in Fig. 2a and implemented in Fig. 2h, each InP chip was accessed using three single-mode fibres: one for reference seed (signal) input/output, and two for quantum seed (signal) input/output. The coupling loss between chip and fibre vary between different samples, but the typical value is around 4 dB per facet. For future large-scale deployment, standard fibre-array packaging can be adopted to enhance operational stability and user accessibility. Laser diode controllers were used to control the SOA section of on-chip DBR lasers and the chip's temperature, and the DBRs were controlled with additional voltage sources. The frequency detuning with the microcomb seed light could be carefully controlled to achieve injection locking conditions. The detuning range was initially determined by synchronously adjusting above operating parameters to make robust injection-locking operation. Subsequently, with all parameters maintained constant, stable locking states can be reliably achieved during each experimental run through rapid SOA current scanning until reaching predetermined values. *For example, the input seed power was carefully set constantly to a minimum of -20 dBm on-chip to ensure the stable injection-locking.* Such procedures

c. When the authors mention “simultaneously deployed”, how many clients are connected to the sever node at any point in time? It is understood that light from the server microcomb is split into 20 downstream fibres simultaneously. How much power reaches each client in the case of short and long downstream fibres?

Author Reply 2(c): As shown in Fig.1 and analysed in Supplementary Information Section 4.3 regarding phase fluctuations induced by downstream fibres, the users in the WDM-based TF-QKD network share common long-haul backbone fibres for downstream and upstream transmission. Consequently, the microcomb output at the server is not directly split into 20 fibre channels. Instead, it is divided into two parts (serving Groups A, B, respectively), each of which is transmitted through the corresponding long downstream fibre (two fibres in total), and then wavelength-demultiplexed at the intermediate node. To better represent the actual experimental setup and align more clearly with the network schematic, **we have updated Fig.S5 (Fig. S3 in the first revision), see Box 4.**

Although 20 independent client-side InP chips were employed in this work, we emphasised that the parallelism was currently demonstrated in a compromised manner to evaluate performance—an approach that has also been acknowledged by the Referee. Thus, the scheme can be understood as follows: in each instance, 2 “real” users and 18 “virtual” users are simultaneously connected to the server node. This implies that the server must distribute at least 10 wavelength channels into the downstream fibres. After wavelength-demultiplexing at the intermediate node, the selected user pair performs injection locking and quantum state encoding with the corresponding reference and quantum wavelengths, while the remaining wavelength channels are left unmodulated. These unmodulated signals are then multiplexed with the user-encoded signals for transmission through

the shared upstream fibres. Finally, at the server side, only the encoded wavelength channels are selected for detection in TF-QKD, while the remaining channels are left undetected (see Box 4). As clarified in Supplementary Information Section 4.1, an on-chip seed power of around -20 dBm is required to achieve injection locking (we retained the highlighted text in the 2nd revision, see Box 3). We would like to emphasise that for all experimental configurations, including different downstream fibre lengths and different user pairs (i.e., wavelength channels), we endeavoured to maintain a relatively balanced on-chip seed power. Since the coupling losses vary slightly across chips and the operating conditions of the lasers also differ marginally, each case needs individual calibration. It should be noted, however, that such calibration only needs to be performed once: once the operating point is identified, it can be set as a fixed parameter. Under consistent operating conditions, e.g., coupling efficiency, chip temperature, there's no need for further recalibration. Considering a coupling loss of about 4 dB, the decision on whether to employ an EDFA, as well as the required amplification stages, is dependent on the initial comb power and transmission losses in the cases of long-haul or short-haul downstream fibres (please see discussion in Supplementary Information Section 5.1. **Please also see our response to the Referee's comment 4.)**)

Box 4: updated Fig.S5

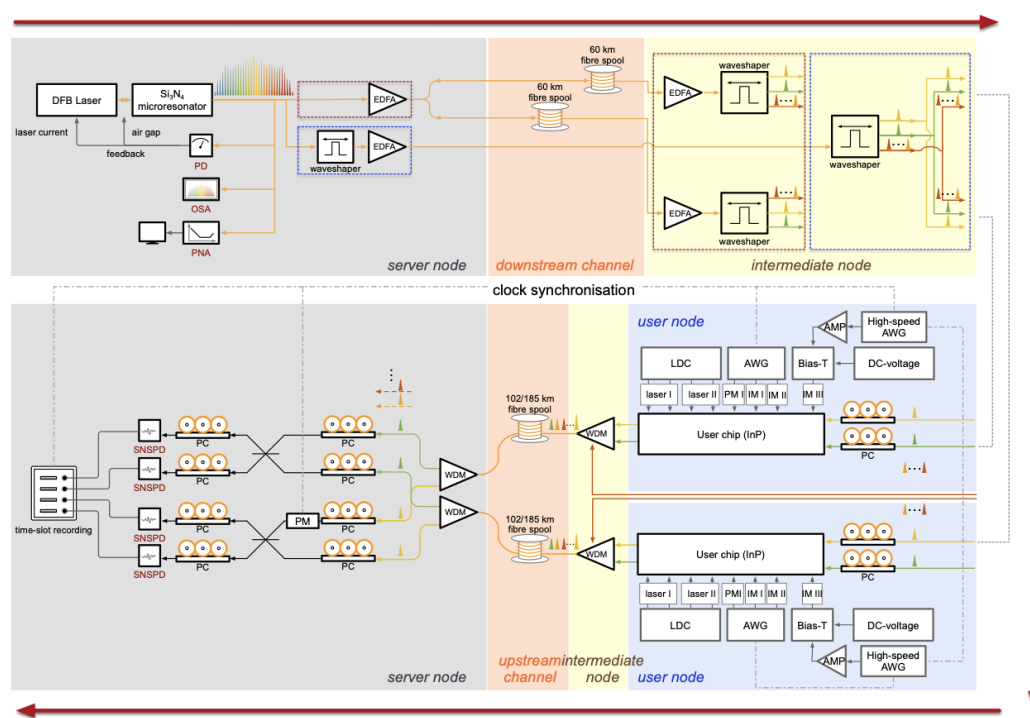


Figure S5 A full diagram of the experimental setup for TF-QKD between paired QKD client-chips in the network. The TF-QKD network between 20 client chips centralised with a microcomb laser, which provides all chip-level resources required for parallel and simultaneous 20-client QKDs in the network. We implemented sequential measurement on these 20 independent TF-QKD chips through 10 WDM channels because of the limited resources, such as radio-frequency (RF) electronic controls and synchronisations in the laboratory. The diagrams for the Hz-level linewidth microcomb and QKD chips are shown in Fig.2 of the main text. This diagram provides a system-level overview of paired QKD client-chips, focusing on both optical paths and electrical controls. The experimental configurations for both long-haul and short-haul downstream fibre cases are presented side by side. The red dashed box denotes the experimental setup with the long-haul downstream fibre, in which spectrum equalisation at the server node was omitted and additional optical amplifications were applied at the intermediate node. The blue dashed box represents the short-haul downstream fibre case, where, as the downstream fibre length is approximately zero, both power distribution and wavelength allocation were carried out at the intermediate node. PD: photodiode, OSA: optical spectrum analyser, PNA: phase noise analyser, EDFA: Erbium-doped fibre amplifier, PC: polarisation controller, AWG: arbitrary waveform generator, AMP: electrical amplifier, LDC: laser diode controller, WDM: wavelength-division multiplexer, SNSPD: superconducting nano-wire single-photon detector, PM: phase modulator, IM: intensity modulator.

New text in Fig.2 caption:

Figure 2 Integrated photonic microcomb and QKD transmitter chips. (a), Schematic diagram of chips and networks. Server-chip microcomb with Hz-level linewidths is used to drive and phase-lock slave lasers on QKD client chips separated at metropolitan areas A & B corresponding to group A & group B chips. Client chips locally regenerate low-noise light field for phase reference (at λ_0 , yellow pulses) and weak coherent states for quantum key coding (at λ_i , coloured pulses) using phase-locked slave lasers. Paired client-chips of $\{A_i, B_i\}$ send quantum states through the λ_i -channel in long-haul upstream fibres (where all wavelength channels are multiplexed), with single-photon interference measurements at the server node returning secure keys. A complete setup diagram is provided in Fig.S5. (b), Device and experimental setup of integrated microcombs by self-injection-locking a DFB laser to a Si_3N_4 ultra-high-Q

Reviewer Comment 3, Downstream link and WDM:

It is mentioned that “for the {A5, B5} chips 120 km (60 km + 60 km) fibres were used to characterise the network with realistic long downstream fibres”. Is that:

- a. 120 km in total for each downstream fibre as suggested by the caption of Fig 3f,3g “predominantly short downstream links, except for the {A5, B5} paired QKD which adopted 120 km downstream fibres”*
- b. 60 km for A5 and 60km for B5, with both comb lines in each fibre? In this case:*
- i. The authors should clarify in the caption that the phase drift is measured after propagation in a 60 km long fibre.*

Author Reply 3(i): We sincerely appreciate the reviewer’s suggestions on network configurations. In our manuscript, when we refer to the downstream fibres, we mainly mean the backbone fibres, whose length could reach the order of hundreds of kilometres in practical scenarios. In the current two-user-group (Group A+B) cases, there are two sets of such backbone fibres to connect the server node and intermediate nodes of each user group; therefore, we describe the long downstream fibre scenario as consisting of 60 km + 60 km fibres. That means, at the server node, the comb lines are first equally divided into two parts, and then all the required comb lines (10 quantum wavelength channels + 1 reference wavelength channel here) are co-transmitted through the two backbone fibres to the intermediate nodes, where wavelength demultiplexing is performed. In fact, the two downstream backbone fibres are fully independent and physically separated, and the connections between different user groups must traverse both fibres. The phase fluctuation is evaluated by comparing the phase differences of the comb lines after transmission through both fibres, rather than the phase difference introduced by either one alone. That is, the phase drift is measured after propagation in the 60 km+60 km long downstream fibres and 185 km + 185 km long upstream fibres. This is a valid point regarding fibre length representation. In line with the conventional representation used for upstream fibres, the downstream fibre length should indeed be calculated as the sum of the two fibre segments connecting the user pairs. We thus prefer to retain the current description, i.e., a 120 km (60 km + 60 km)-long downstream fibre.

- ii. The authors should comment on the feasibility of tracking the accelerated phase shift over fibres that are 3 times longer. From Fig 3d [A5,B5], ϕ_d seems to drift significantly faster than with short downstream fibres, so it’s not clear whether the same postprocessing approach would still be able to cope with 185 km downstream fibre per client.*

Author Reply 3(ii): We sincerely appreciate the reviewer’s thoughtful comments regarding the completeness of our discussion on symmetric upstream and downstream fibre configurations. As noted in previous works such as the seminal TF-QKD paper [*Nature* 557, 400–403 (2018)], longer fibres lead to faster phase drift rates, which generally scale with $\sqrt{L}$ according to the random-walk phase noise model. Therefore, the phase difference ϕ_d also varies more rapidly over extended transmission distances. Since ϕ_d is derived by comparing ϕ_r and ϕ_q in the post-processing-based dual-wavelength phase-tracking method, the primary requirement is the ability to track the single-wavelength phase in real time. Reported phase drift rates in long-haul fibre channels include 14.470 rad/ms over a 1690 km fibre MZI with symmetric downstream and upstream fibres in a lab environment [*Nat. Photon.* 16, 154–161 (2022)] and 7.80 rad/ms over an 856 km (428 + 428 km) symmetric fibre link in a field test [*Phys. Rev. Lett.* 126, 250502 (2021)]. Assuming a phase drift rate of 15 rad/ms, the requirement to avoid introducing significant phase estimation errors is to

perform a phase estimation approximately every 0.02 ms (which could be regarded as a sampling rate of 50 kHz, not that fast), corresponding to a phase variation of about 0.3 rad. Noting that, the phase estimation method relies on the accumulated counts of single-photon detectors. To suppress the statistical errors arising from the Poisson distribution of photon numbers, around 100 counts in one estimation period would be preferred. This corresponds to a maximum count rate of 5 MHz for the single-photon detectors—a requirement readily met by nowadays high-speed, low-noise superconducting nanowire single-photon detectors (SNSPDs). Thus, from a technical standpoint, implementing dual-wavelength phase tracking over longer fibres is entirely feasible, and in fact has already been experimentally validated. One notable example is the 1000 km TF-QKD experiment [Phys. Rev. Lett. 130, 210801 (2023)], in which the downstream and upstream fibres formed a MZI exceeding 1800 km in total length, and effective phase tracking was successfully achieved under such conditions. In our network, the system operated normally under the long downstream fibre condition, indicating that the additional noise arising from amplification and nonlinear effects does not impair the locking process (Supplementary Information section 5.1), and that the accelerated phase fluctuation has no observable impact on injection locking or the overall phase tracking. Therefore, we can reasonably and optimistically infer that the integrated-photonics-based network remains effective and feasible even for longer fibre links. To address the referee's point thoroughly, we have included an additional description in the Supplementary Section 4.3 (see Box 5).

Box 5: new paragraph in Supplementary Information Section 4.3:

For future quantum networks with extended distances, the phase fluctuation (ϕ_r and ϕ_d) will accelerate. According to the random-walk model of phase drifts in the fibre, the drift rate generally scales with $\sqrt{L}$ of the fibre length¹⁵. The phase differences ϕ_d of dual- λ will also vary more rapidly, as the optical path fluctuations have slight different impact on different wavelengths. The faster fluctuation of ϕ_r , ϕ_d and ϕ_d has been experimentally observed in the short and long downstream fibre scenarios in Fig. 3. For the short downstream fibre case, the downstream and upstream fibre channels form a MZI with the arm length of 370 km (370 km + 0 km), while the long downstream fibre case has the arm length of 490 km (370 km + 120 km). The measured phase drift rates of $\{\phi_r, \phi_d\}$ are {2.871, 0.033} rad/ms for the former case and {3.908, 0.069} rad/ms for the latter. Results from the literature show the phase drift rate of 14.470 rad/ms with 1690-km-long fibre MZI consisting of symmetric downstream and upstream fibres in the lab¹⁹, and 7.80 rad/ms with 856-km-long (428 km + 428 km) symmetric fibre channel in the field test⁸⁵. For the post-selection approach adopted in this work to realize phase tracking, the key lies in effectively recovering the phases ϕ_r and ϕ_d , while the phase difference ϕ_d can be directly calculated. A faster phase drift implies that a higher sampling rate is required for phase tracking. Since each data point relies on the accumulation of single-photon counts at the server node (see section 4.5 for details), this in turn means that a sufficient number of single-photon counts must be obtained within a short time window to suppress the statistical errors arising from the Poisson distribution of photon numbers. Assuming a phase drift rate of 15 rad/ms, the average requirement to avoid introducing significant phase estimation errors is to perform a phase estimation approximately every 0.02 ms, corresponding to a phase variation of about 0.3 rad. This means we have to accumulate around 100 single-photon counts in 0.02 ms, which corresponds to a max count rate of 5 MHz for the SNSPD. This value could be met by the high-speed low-noise SNSPDs nowadays. In fact, even when the fibre channel length increases to the order of one thousand kilometres, the phase tracking could still be effectively implemented with dual- λ method and postselection²⁰. Similarly, in our case, it could be expected that the extended fibre length will not introduce troublesome experimental failures. We simply need to adjust the comparison period according to the actual conditions, just as we reduced the period to 2 ms out of 5 ms in the case of longer downstream fibres.

Reviewer Comment 4, Wavelength division demultiplexing:

Looking at Fig. 1, Fig. S3, and the comment it is difficult to understand where and how the demultiplexing of the reference and OIL comb lines is done.

Author Reply 4: We sincerely thank the Referee for pointing out the insufficient description of the experimental details. We recognised that the experimental setup Fig. S3 (now Fig. S5 in the 2nd revised version, see Box 3) does not clearly present all key experimental components, particularly those related to WDM. Accordingly, following the reviewer's suggestion, we have now revised and supplemented Fig. S5 and added additional explanations in the revised manuscript, as follows.

a. Section 'Architecture of the TF-QKD network' proposes: "Microcomb lines are dispersed across the network via the backbone fibres and wavelength-demultiplexed at intermediate nodes before reaching the client-side chips."

i. Is this precisely what is done in the experiment or is this a vision for a TF-QKD network

implementation?

ii. In Fig S3, wave shaper II is used to send the reference and quantum lines to a specific client pair, but it is not clear what happens to the other microcomb lines and the other downstream fibres.

b. Fig. 3 caption: “while maintaining continuous operation of all other wavelengths multiplexed in the same fibres”. This suggests that the client is aligned to the microcomb line of interest for OIL without the need of filtering the other lines.

c. At the same time, page 4 explains “with each client-chip receiving two microcomb lines as seeds to implement the dual- λ phase tracking [18]” which seems to contradict the statement in Figure 3. Where in the links are the wavelengths demultiplexed? Which wavelength is sent to which node?

Author Reply 4(a-c): In the revised Figure S5, we have improved the presentation to more clearly distinguish the functional roles of each node. The new Fig.S5 now uses distinct background shading to differentiate the 3 core parts: the server node (generating microcombs and performing single-photon detection), the intermediate node (handling wavelength allocation in the WDM scheme), and the user nodes (for quantum and reference light regeneration and encoding).

We present the experimental configurations for both the long and short downstream fibre cases side by side. The red dashed box denotes the experimental setup using the long downstream fibre, where spectrum equalisation at the server node was omitted and additional optical amplifications were applied at the intermediate node. The blue dashed box represents the short downstream fibre case. Given that the downstream fibre length is approximately zero in this case, both power distribution and wavelength allocation were carried out at the intermediate node. As shown, the long downstream fibre configuration aligns more closely with the architecture in Fig.1 and better represents the setup expected in real-world deployment scenarios.

The entire process can be regarded as a loop consisting of the following sequence: server node → long downstream backbone channel → intermediate node → user node → intermediate node → long upstream backbone channel → server node. In principle, for each user, the required reference and quantum wavelengths are allocated at the intermediate node and transmitted to the user node through the same fibre. They are then demultiplexed again to lock the on-chip lasers separately. As shown in Fig. S5, in our implementation, the intermediate node directly selects the reference and quantum wavelengths required by the user under test and transmits them separately to the user node through different fibres. In practice, this means we omitted the short fibre link between the intermediate node and the user node. The only distinction lies in whether an additional multiplexer for wavelength demultiplexing (and subsequent remultiplexing) is placed at the user node. In future implementations using microcomb seeds aligned with ITU wavelength channels, standard multiplexers can be deployed cost-effectively at the user node or even monolithically integrated on-chip, presenting no significant barrier to scalability.

For the remaining wavelengths, we multiplexed them into a single fibre and then remultiplexed them with the quantum and reference signals of the TF-QKD users for transmission through the same upstream fibre, as indicated by the red arrows following the waveshapers at the intermediate node in Fig. S5. Since our motivation was to evaluate the noise arising from parallel transmission under the worst-case scenario, these unmodulated wavelengths have been intensity-adjusted during the downstream transmission by the waveshaper filters at the intermediate node, in accordance with the evaluation conditions described in Supplementary section 4.4.

We believe that the referee’s concerns (a-c) on WDM have been well addressed by revising Fig. S5 and including additional explanations in the Supplementary Information section 4.1. We prefer to

keep a simple description in main text and explain technical details in Supplementary Information, just to balance the broad accessibility with specialist rigour. See modifications in Box 6.

Box 6: revision in Supplementary Information Section 4.1:

WDMed Quantum channels in fibres: As shown in Fig.S5, the process can be regarded as a loop consisting of the following sequence: server node → long downstream backbone channel → intermediate node → user node → intermediate node → long upstream backbone channel → server node. For each QKD user, the required reference and quantum wavelengths are allocated at the intermediate node and transmitted to the user node through the same fibre. The upstream channel distance from Alices' and Bobs' node to the central server node and corresponding fibre losses are provided in Table S3. Constrained by limited RF resources, we simulated concurrent multi-user communication by implementing the whole quantum state encoding procedure in sequence for the selected user pair while leaving other non-target wavelength signals unmodulated and directly injecting into the upstream fibre channels. To evaluate worst-case crosstalk, these non-target wavelength signals were maintained at maximum intensity levels required for phase tracking (see Section 4.3). As shown in Fig.S5, the short/long downstream fibre cases show slightly different configurations. We used dashed boxes in two colours—red for the long downstream fibre case and blue for the short case—to indicate the different experimental conditions. Due to limited resources, spectrum equalisation at the server node was omitted in the long downstream fibre configuration and additional amplifications were conducted at the intermediate node. In our implementation, the intermediate node directly selects the reference and quantum wavelengths required by the user under test and transmits them separately to the user node through different fibres. In practice, this means we omitted the short fibre link between the intermediate node and the user node. The only distinction lies in whether an additional multiplexer for wavelength demultiplexing (then remultiplexing) is placed at the user node. For the remaining wavelengths, we multiplexed them into a single fibre and then remultiplexed them with the quantum and reference signals for transmission through the same upstream fibre, as indicated by the red arrows following the waveshapers at the intermediate node in Fig. S5. To simplify the system for a proof-of-principle demonstration of TF-QKD network, the downstream fibres from the microcomb to the QKD client-chips were replaced by short fibres in most cases, except for the user pair $\{A_5, B_5\}$, where 120 km-length (60+60 km) downstream fibres were used. Moreover, we confirm comparable phase drift and phase tracking for short and long downstream fibres in Fig.3 and implement TF-QKD in both cases in Fig.4. Detailed performance characterisation regarding the introduction of long downstream fibres is presented in the main text and further discussed in Section 5.1.

revision in Fig.S5 caption:

Figure S5 A full diagram of the experimental setup for TF-QKD between paired QKD client-chips in the network. The TF-QKD network between 20 client chips centralised with a microcomb laser, which provides all chip-level resources required for parallel and simultaneous 20-client QKDs in the network. We implemented sequential measurement on these 20 independent TF-QKD chips through 10 WDM channels because of the limited resources, such as radio-frequency (RF) electronic controls and synchronisations in the laboratory. The diagrams for the Hz-level linewidth microcomb and QKD chips are shown in Fig.2 of the main text. This diagram provides a system-level overview of paired QKD client-chips, focusing on both optical paths and electrical controls. The experimental configurations for both long-haul and short-haul downstream fibre cases are presented side by side. The red dashed box denotes the experimental setup with the long-haul downstream fibre, in which spectrum equalisation at the server node was omitted and additional optical amplifications were applied at the intermediate node. The blue dashed box represents the short-haul downstream fibre case, where, as the downstream fibre length is approximately zero, both power distribution and wavelength allocation were carried out at the intermediate node. PD: photodiode, OSA: optical spectrum analyser, PNA: phase noise analyser, EDFA: Erbium-doped fibre amplifier, PC: polarisation controller, AWG: arbitrary waveform generator, AMP: electrical amplifier, LDC: laser diode controller, WDM: wavelength-division multiplexer, SNSPD: superconducting nano-wire single-photon detector, PM: phase modulator, IM: intensity modulator.

clarification in Fig.3 caption in main text:

collected sequentially for each pairwise linked QKD chips at their wavelength channels, while maintaining continuous operation of all other wavelengths multiplexed in the same fibres (filtered out before injection-locking the microcomb lines of interest). (e), An example of phase distributions for the $\{A_1, B_1\}$

Reviewer Comment 5: *The mean photon number in the Z basis is greater than 0.5. It would be useful that the author comment on this choice, as it might affect the protocol security by increasing the risk of multi-photon events.*

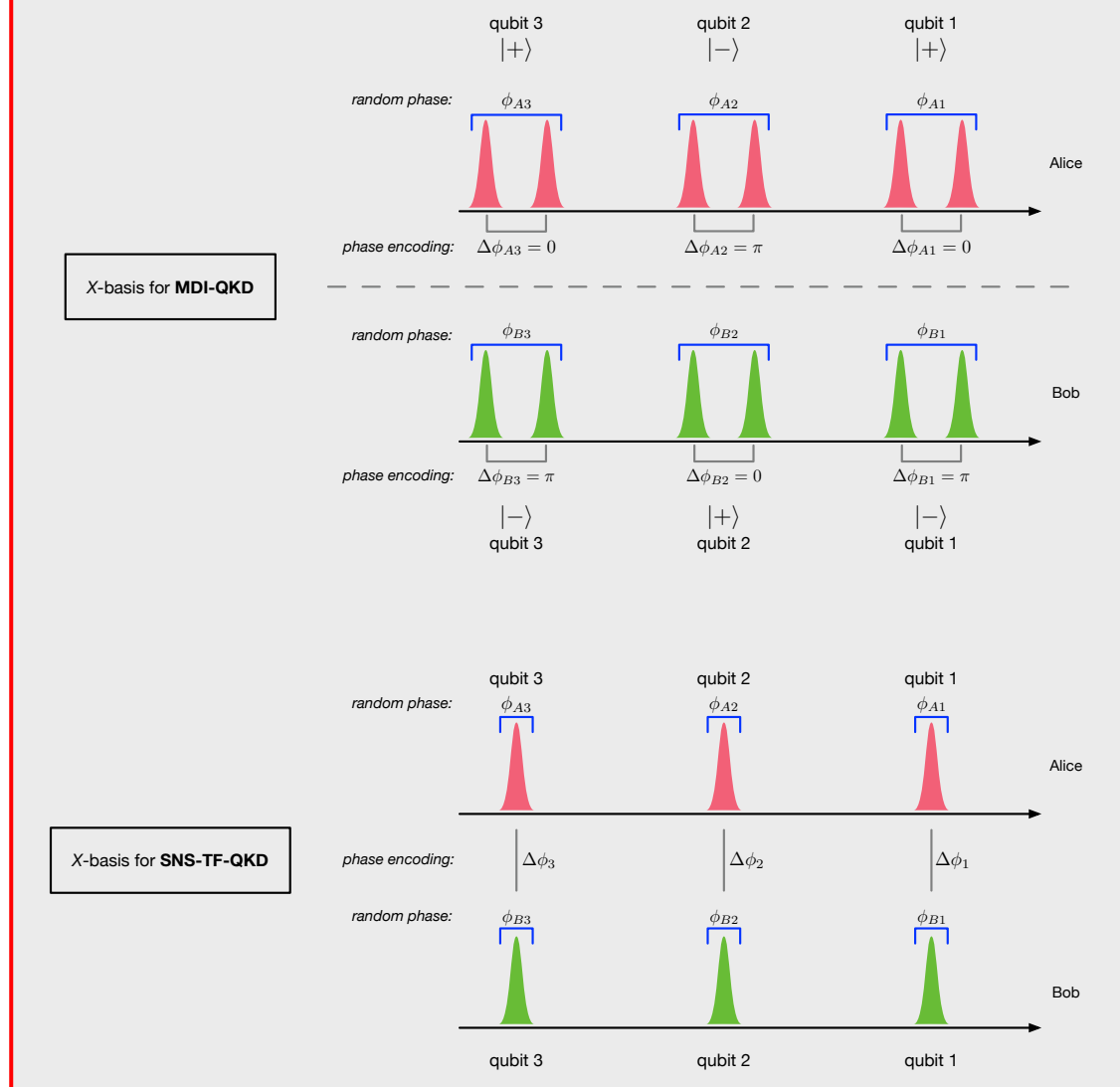
Author Reply 5: We thank the referee very much for carefully reviewing our work. For QKD based on weak coherent states, one of the most significant vulnerabilities is the photon-number-splitting attack targeting the multi-photon components. Fortunately, this limitation is lifted by the *decoy-state method*, and in a short time, this method has become a standard procedure in almost all QKD implementations, including our work here. The core idea of the *decoy-state method* is as follows: the users randomly transmit phase-randomised weak coherent states with different mean photon numbers. Because Eve cannot discriminate which pulses are decoys, he applies a uniform photon-number-splitting attack to all states; this produces different responses for the different decoy settings. Through comparing the detection statistics, Eve's attack can be revealed, and the genuine secure information carried by the single-photon components can be extracted by means of privacy amplification. Thus, whether relatively high mean-photon-number coherent states are employed does not directly determine the security of the *decoy-state method*. Typical values of mean photon number in the Z basis could be found as: 0.445 for the 1000-km TF-QKD experiment [*Phys. Rev. Lett.* 130, 210801 (2023)]; 0.422 for the 511-km TF-QKD field test [*Nat. Photon.* 15, 570–575 (2021)]; 0.52 for the TF-QKD in the deployed network [*Nature* 640, 911–917 (2025)]. Thus, the choice of relatively high mean photon number in the Z basis would not degrade the security, on the contrary,

it would increase the secure key rate as we get more effective events due to a larger single-photon emission probability.

Reviewer Comment 6: An important point of concern is the phase randomization/encoding approach. The authors should clarify how the phases between Alice and Bob are randomized with respect to one another while all the electronic signals are synchronized. The current explanation is that a sawtooth pattern is applied to the PM during 15 ms of quantum communication while the IM is carving pulses at 200 MHz, yielding 3 million different phases.

Author Reply 6: We appreciate the referee's insightful comment on experimental implementations of the phase randomisation/encoding by modulating the quantum states throughout the protocol. This is a nuanced yet crucial technical consideration. In fact, phase randomisation is fundamentally required by the decoy-state method, while phase encoding typically refers to the intentional phase applied to specific quantum states, e.g., when selecting the X basis in conventional QKD protocols. These two processes can be considered different; however, they are operationally interdependent in the implementation of SNS-TF-QKD. This can be well clarified by comparing the implementations of SNS-TF-QKD and MDI-QKD (see Box 7).

Box 7: A comparison of the phase randomisation and phase encoding between MDI-QKD and SNS-TF-QKD.



Taking the implementation of time-bin encoding MDI-QKD as a comparison, when we choose to encode the $|+\rangle$ or $|-\rangle$ state in the X -basis, we modulate the relative phase between the early and late pulse within the same qubit period. In MDI-QKD, once the $\Delta\phi_{A(B)}$ is chosen by Alice (Bob), the expected state could be generated deterministically, thus they finish the phase encoding. At the same time, phase randomisation is always implemented according to the decoy-state requirement, that Alice (Bob) randomly modulates the global phase of one qubit (i.e., the pulse pair of early and late bin). The effects of phase randomisation and phase encoding are independent: the former acts on the qubit as a global phase, whereas the latter applies to the early and late pulses of a qubit, affecting their relative phase.

It becomes different in the SNS-TF-QKD protocol. This is because the phase encoding relies on the relative phase between the twin fields sent by Alice and Bob, or, more precisely, based on the postprocessing approach, the encoding depends on the phase difference observed at the server node according to the interference outcome, after transmission through the upstream fibre (see Eq. S16). As a result, the phase randomisation will inevitably influence phase encoding, and neither Alice nor Bob alone can determine which state in the X -basis has been encoded. This gives rise to a substantial difference from the conventional understanding of quantum state encoding in the X -basis. Actually, in SNS-TF-QKD, the so-called “phase encoding” in the X -basis is also implemented by randomly modulating the phase of the weak coherent states sent by Alice and Bob (which have been detailed discussed in the Supplementary Material of ref. *Phys. Rev. Lett.* 123, 100505 (2019)), which in turn fuse into the procedure of phase randomisation. That's to say, the joint effect of phase randomisation and phase encoding, is to randomly modulate the phase of weak coherent states, and this is why we state that we finish the phase randomisation and phase encoding using one PM with sawtooth voltage scanning. We will provide detailed clarifications and discussions to address the referee's concerns as follows.

a. Why not encode a random pattern on each PM? It's expected that the PM RF bandwidth is high enough for that. What is the limitation?

b. Are the sawtooth patterns applied to PM 1 generated with the same frequency for both clients of a pair A_i, B_i ?

Author Reply 6(a,b): For the phase randomisation implemented in this work, we adopted a fixed waveform scanning method instead of a random pattern for PMs. This approach was necessitated by limitations in the experimental RF resources available in our laboratory, and is not a constraint imposed by the performance of the integrated InP QKD chip or the overall network architecture. For multi-level random phase modulation, the spectral occupancy extends to several times the fundamental frequency f_{re} . To achieve precise phase modulation, a system bandwidth of around 5–10 times the repetition frequency f_{re} (200 MHz in this work) is required. This implies that the RF signal bandwidth for phase modulation must exceed 2 GHz. Due to limited high-speed RF resources in our lab, we adopted a slower fixed sawtooth scanning method in place of a random multi-level sequence as a practical compromise.

The sawtooth waveforms applied to the phase modulators for both clients in a given pair $\{A_i, B_i\}$ are generated at the same frequency.

Moreover, we would like to emphasise that, as a proof-of-principle experiment, the primary focus of this work lies in evaluating the performance, scalability, and stability of the integrated quantum photonic chips implementing high-performance quantum communication protocols, as well as in

validating the overall multi-user network architecture built upon them. Closing all these potential loopholes is beyond the scope of our current study; however, we agree with the Referee, it is indeed necessary to discuss whether the hardware is capable of comprehensively implementing QKD. For phase randomisation required by the decoy-state method, two aspects are essential:

- (1), applying random phases to the encoded quantum states;
- (2), ensuring the applied phases behave as intended.

The latter (2) basically involves verifying whether the phase modulator introduces any noticeable signal distortion, which necessitates a thorough bandwidth analysis. In the revised manuscript, we have now performed new measurements of the eye-diagram to characterise the phase modulator and have included the result in Supplementary Information Section 4.2 and Fig. S7(c,d) (see Box 8). The clear eye diagram in Fig.S7d shows that the phase modulator could completely meet the bandwidth requirement in this work with 200 MHz repetition frequency. We would like to emphasise that the expected bandwidth of the device far exceeds current conditions (approximately 25 GHz under ideal conditions from foundry tests). The test at this low frequency

Box 8: revision in Supplementary Information Section 4.2:

tion has been achieved, thereby enabling an accurate evaluation of the system performance. Then, we performed a brief bandwidth test of the phase modulators on chip to demonstrate the multi-level encoding accuracy in a high speed system. The measurement was performed using a MZI configuration, as illustrated in Fig.S7c.: A low noise laser is split into two arms, one of which is sent through the InP client chip with the integrated phase modulator driven by AWG, and the other is left going directly through the fibre channel. Then, they are combined with aligned polarisation for interference, and the results are detected by a high-speed photodiode and acquired by a real-time oscilloscope. The modulation signal is a seven-level pattern with a symbol rate of 200 MHz. According to Ref.[83], 12 discrete randomisation phase slices are enough to approximate the ideal case of infinite level. However, the interference result would not distinguish between phase differences of $[0, \pi)$ and $[\pi, 2\pi)$, so we set a 7-level pattern covering $[0, \pi)$ to avoid confusion, which is enough for bandwidth certification even on its own. A clean and symmetric eye opening is observed, indicating that the modulator preserves signal integrity across multiple

phase levels. The well-resolved eye pattern confirms that the device possesses adequate bandwidth to accommodate high-speed multi-level modulation schemes. A slight broadening observed in each amplitude level of the eye diagram can be attributed to the combined effects of the high-speed PD's low responsivity, amplitude noise of our oscilloscope and time-fluctuating bias point of the fibre-based MZI. According to the result above, we can claim a sufficient bandwidth of the phase modulator to perform fully random encoding in this system. In our

A new Fig.S7:

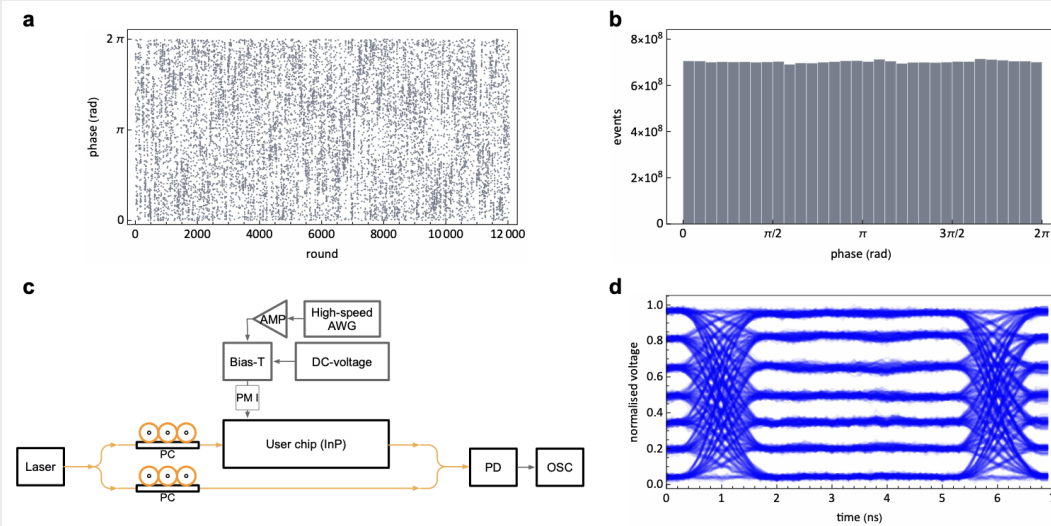


Figure S7 Device and system characterisations for the phase randomisation verification. (a), Experimental results of $[(\delta_{A,r} - \delta_{B,r}) - (\phi_{B,q} - \phi_{A,q})]$ for paired QKD users $\{A_1, B_1\}$ during quantum communication at the distance of 370 km. The first 12,000 round was displayed, with each round denote one phase estimation points lasting 100 μ s. (b), Phase distribution of $[(\delta_{A,r} - \delta_{B,r}) - (\phi_{B,q} - \phi_{A,q})]$ for $\{A_1, B_1\}$ when they both choose the intensity of v_1 . Totally 225×10^8 such events were sent. Note that, $[(\delta_{A,r} - \delta_{B,r}) - (\phi_{B,q} - \phi_{A,q})]$ determines an X-basis event and it is uniformly distributed over $[0, 2\pi)$, while the reference phase difference $\phi_d = [(\phi_{B,r} - \phi_{A,r}) - (\phi_{B,q} - \phi_{A,q})]$ (shown in Fig.3 in main text) is highly correlated over time and it is used to estimate phase fluctuations in the fibre channels. (c), Experimental setup for eye-diagram characterisation of the integrated phase modulator. (d), The eye diagram obtained from accumulating 1000 waveform frames, acquired by a real-time oscilloscope operating at 10 GSa/s.

new text in revised main text (page 4):

in Supplementary Information 1). An eye-diagram to characterize the PM bandwidth is provided in Fig.S7. Further, the original DBR

was conducted as a verification based on a consideration of the available experimental equipment in our lab and the overall TF QKD system bandwidth requirements. It can be trusted that the integrated quantum photonic chip possesses sufficient modulation bandwidth to apply random phases.

The remaining question then concerns the first point—whether truly random signals are applied. We'll address this point in the response to the following comments and suggestions.

c. In SI 4.2, it is stated that: "For a proof-of-principle experiment, the preset repeated phase sequence effectively emulates the random phase settings [74]. The random phase and the encoding phase always work as a whole. We can consider the sawtooth voltage as providing phase randomisation and encoding phase at the same time, which would not affect the result while simplifying the implementation." This seems to mean that the authors consider the sawtooth pattern as being random and encoded phase at the same time, however it doesn't explain how different phases are sent from both clients for a given X event.

d. This question is important because in a situation where all X basis events are matched in phase (i.e. always falling in the same phase slice, hence aligned in encoded and randomized phase), two issues could invalidate the SKR estimation, and the violation of the PLOB bound, even for a proof-of-principle experiment:

i. A situation with encoded phases being always well aligned with each other would increase N_{Δ} (see Eq S16, S20) which may lead to a strongly underestimated phase QBER, in turn yielding an overestimated SKR.

ii. The number of X detections required to bound the phase QBER could be smaller than in a real-case scenario, so the finite size analysis, as presented, could also yield an overestimated SKR.

e. One could imagine that the fibre drift is used to decorrelate the phases, but as shown in 2e, due to the very high quality and coherence of the microcomb, the phase drifts of the reference and quantum line are strongly correlated and the resulting phase difference barely drifts within the 15 ms of quantum communication, so the phases of both clients would always be in the same slice.

f. The authors may have implemented X events that are not correlated in phase, but it is not clear how, from the current description. This should be clarified to the readers, especially those familiar with TF-QKD. A plot of the distribution of $[(\delta_A - \delta_B) - (\phi_B - \phi_A)]$ after postprocessing would be helpful.

Author Reply 6 (c-f): We would like to first recall the phase randomisation procedure in the *decoy-state method*. The requirement for "random phases" can be divided into two key aspects: (1), The global phases of the transmitted states need to be uniformly distributed on 0 to 2π , so the signal states could be treated as fully mixed photon number states, and we can apply gain analysis to extract the secure single photon components. (2), These global phases should remain undecipherable by any third-party eavesdropper, which means that Eve would obtain again a uniform distribution over $[0, 2\pi)$ regardless of any phase compensation she may attempt (at least her probability of guessing the correct phases is sufficiently small). In other words, the phases should be non-predictable.

It can be recognised that, in a statistical sense, a fixed-period sawtooth phase scan satisfies the first condition—transforming the weak coherent state into a photon-number mixed state and thereby ensuring the computational correctness of single-photon yield estimation in *decoy-state* analysis.

The central question then lies in the second requirement: the phase is not truly random. Under standard QKD security assumptions, only true random numbers—or in physical implementations, quantum random numbers—are considered secure. In this regard, methods such as algorithmically generated pseudo-random numbers, repeated random sequences, or a simple sawtooth sweep do not differ significantly in terms of their vulnerability. While the generation of quantum random numbers has been demonstrated on integrated platforms [e.g., *Nat. Electron.* 7, 396–404 (2024)], integrating such a module into the current system would introduce considerable complexity and overhead, especially given the substantial scope of the present study. Therefore, we believe that for a proof-of-principle experiment, the use of a fixed sawtooth scan, together with full modulator bandwidth verification, sufficiently demonstrates that full phase randomisation is realisable in practice.

The final issue is thus whether the key rate can be correctly estimated—specifically, the Referee's concern regarding whether X -basis detection events always fall within the same phase slice.

We would like to revisit the definition of X -basis events in SNS-TF-QKD, particularly in the context of the fibre channel phase post-processing configuration [*Phys. Rev. Lett.* 123, 100505 (2019); *Phys. Rev. Lett.* 130, 210801 (2023)], rather than the compensation method. As shown in Box 7, the phase encoding depends on the collective choice of Alice and Bob, not solely on anyone. Importantly, in the post-processing case, X -basis events are defined as effective detection events that satisfy an additional specific requirement: the phase difference between the quantum states sent by Alice and Bob upon reaching the server node must meet the condition given in Eq. (S16) [*Phys. Rev. Lett.* 123, 100505 (2019); *Phys. Rev. Lett.* 130, 210801 (2023)]. This means the phase we care about is:

$$[(\delta_{A,q} - \delta_{B,q}) - (\phi_{B,q} - \phi_{A,q})],$$

where $\delta_{A(B),q}$ are controlled by Alice and Bob, and $\phi_{A(B),q}$ are determined by the whole fibre links traversed by the quantum states. Non-random phase encoding of $\delta_{A(B),q}$ may destroy the assumption of uniform distribution in $[0, 2\pi)$, but the random fluctuation of $\phi_{A(B),q}$ makes the whole term of $[(\delta_{A,q} - \delta_{B,q}) - (\phi_{B,q} - \phi_{A,q})]$ still distribute uniformly within the range of $[0, 2\pi)$ as shown in our experimental results added in Fig.S7a,b (Box 8). There could be a misunderstanding of the phase difference between reference signal and quantum signal, as shown in Fig.3d and Fig.3e, where $\phi_d = \phi_r - \phi_q = [(\phi_{B,r} - \phi_{A,r}) - (\phi_{B,q} - \phi_{A,q})]$. The differential phase ϕ_d is expected to vary slowly over time, since both $(\phi_{B,r} - \phi_{A,r})$ and $(\phi_{B,q} - \phi_{A,q})$ are highly correlated—both reflecting phase fluctuations in the same fiber channel, with minor variations due to dispersion. Thus, we believe the Referee's concern that phase correlations might cause the phase differences to consistently align, thereby always falling into the same phase slice, can be effectively addressed.

In summary, the quantity that determines an X -basis event is

$$[(\delta_{A,q} - \delta_{B,q}) - (\phi_{B,q} - \phi_{A,q})], \text{ uniformly distributed over } [0, 2\pi).$$

Meanwhile, the reference phase difference:

$$\phi_d = [(\phi_{B,r} - \phi_{A,r}) - (\phi_{B,q} - \phi_{A,q})]$$

is highly correlated over time and is used to estimate phase fluctuations in the fibre channels.

To avoid any misunderstandings, we have now added subscripts of q and r for the phase describing the quantum and reference signal throughout the revised manuscript. As the referee suggested, we have added a plot of the $[(\delta_{A,q} - \delta_{B,q}) - (\phi_{B,q} - \phi_{A,q})]$ distribution for the {A_1, B_1} paired chips in the 370 km case in a new Fig.S7(a,b) (see Box 8). And we have clarified the difference of ϕ_d and

$[(\delta_{A,q} - \delta_{B,q}) - (\phi_{B,q} - \phi_{A,q})]$ in the Fig.S7 caption (Box 8). We have revised the Supplementary Information Section 4.2 and the main text to further discuss and clarify this point (see Box 9).

Moreover, it could be found that the phases are distributed uniformly in $[0, 2\pi)$, which implies that not all events in which both Alice and Bob select the intensity ν_1 will result in effective X-basis events. Actually, there are 225×10^8 events when Alice and Bob both chose intensity ν_1 . For the $\pi/16$ phase slice adopted in our simulation, an average of $(\pi/16/2\pi \times 225 \times 10^8) = 7.03 \times 10^8$ events are expected to fall within each slice, which is in excellent agreement with our experimental results. Therefore, we have not overestimated $N_{\Delta+(-)}$. The finite-size analysis is valid, and the error test for the X-basis reflects faithfully the misalignments arising from the finite width of the phase slices, imperfect phase tracking, and other hardware-related factors.

Box 9: revision in Supplementary Information Section 4.2:

4.2 Phase randomisation for implementing the decoy state method

Phase randomisation is essential for the decoy state method using weak coherent state sources. In the experiment, the random encoded phase $\delta_{A(B)}$ was set by applying a sawtooth voltage on the phase modulator at the client chip, sweeping from 0 to 2π at one quantum key encoding stage (that is, successive 15 ms in the period of 20 ms). Given the system repetition frequency of 200 MHz, an equivalent discrete randomisation level of 3 million was reached. For a proof-of-principle experiment, the preset repeated phase sequence effectively emulates the random phase settings⁸². The random phase and the encoding phase always work as a whole. We can consider the sawtooth voltage as providing phase randomisation and encoding phase at the same time, which would not affect the result while simplifying the implementation. Statistically, it is equivalent to standard methods that apply random sequences of discrete phase levels as required in decoy states and practical QKD. Thus, statistically, it satisfies the decoy state requirement, and in a proof-of-principle demonstration, it enables accurate inference of single-photon yields according to standard methods with perfect phase randomisation, to eventually obtain correct secure key rate estimations. In the actual QKD scene, it is necessary to use a truly random phase sequence to avoid malicious attack by successfully guessing the phase randomisation information⁸². Figures S7a,b show an example of the experimental obtained distribution of $[(\delta_{A,r} - \delta_{B,r}) - (\phi_{B,q} - \phi_{A,q})]$ during the QKD implementation between the chips $\{A_1, B_1\}$ at the distance of 370 km. To clearly illustrate this, the first 12,000 rounds of phase estimation are presented, where each round represents one phase estimation lasting 100 μ s and comprising 20,000 communication cycles (see Fig. 3a). It could be seen that the phases distributed uniformly in $[0, 2\pi)$. We further present the complete phase statistical distribution for the events where both Alice and Bob select the intensity of ν_1 (see Fig. S7b). It is evident that all events are uniformly distributed across the respective phase slices, demonstrating that, in a statistical sense, the same effect as truly phase randomisation has been achieved, thereby enabling an accurate evaluation of the system performance. Then, we performed a brief bandwidth test of

revision in main text (page 4, 6):

Demonstration of integrated-photonic TF-QKD network

We then implemented a multi-user sending-or-not-sending TF-QKD (SNS-TF-QKD) protocol⁵¹ in this integrated-photonic network. Figure 3a shows the overall experimental process, including system initialisation, quantum key encoding and detection. Note that the reference light signal performs continuous phase estimation, whereas the quantum signal is temporally divided into a phase estimation period—for calibrating the phase difference ϕ_d between the reference ϕ_r and quantum ϕ_q signals arising from slight discrepancies in their optical paths—and a quantum communication period for TF-QKD. Details for the SNS-TF-QKD protocol and experimental implementation are provided in Supplementary Information 4.1.

gated via the use of Hz-level lasers. This was confirmed by the phase difference $\phi_d = [(\phi_{B,r} - \phi_{A,r}) - (\phi_{B,q} - \phi_{A,q})]$ in Fig.3d, revealing slower phase variations. As an example, Figure 3e shows

Reviewer Comment 7, Security analysis:

The authors do not mention any noise rejection routine. In existing implementations of the TF-QKD SNS protocol, two-way classical communication routines such as active odd-parity pairing (AOPP) are used to reduce the bit flip error rate and reach positive SKR. The secure key rate equation is very different from eq. S17. Notable examples where AOPP is used include the 1000-km TF-QKD experiment, where SNSPDs with dark count rates 0.014 Hz and 0.026 Hz were employed [Ref 20], and the TF-QKD without frequency dissemination work [Ref 21], where ultra-stable lasers are employed together with 1 Hz dark count SNSPDs and a field trial [Ref. 22]. Without AOPP, the reported Z QBER (Ez) can easily exceed 25 dB. It is therefore surprising not to see any mention of noise rejection routine in the manuscript.

Author Reply 7: We sincerely appreciate the Referee's suggestion regarding the need to clarify the noise rejection mechanism, particularly in relation to the key rate and the PLOB bound. This aspect represents one of the core advantages of TF-QKD and therefore warrants careful attention. The main factors affecting the experimental key rate at a given distance can be categorised into two parts: (1), the intrinsic limitations of the protocol itself; (2), the imperfections in implementing the ideal protocol—in other words, the practical factors that may lead to an increased error rate.

The intrinsic limitations of the protocol itself: For the original SNS-TF-QKD protocol [*Phys. Rev. A* 98, 062323 (2018)], errors can still occur even assuming perfect experimental conditions (e.g. no dark counts of the detector and misalignment errors) and no eavesdropping. The raw keys can be generated when only one of the legitimate users decides to send the signal pulse in Z-basis, and the other decides not. However, there is always a finite probability that both parties simultaneously decide to send a signal pulse (defined as D bits with a probability of P_s^2), while Charlie ultimately registers a response from only one detector and announces it as a valid event. Such events will cause errors in Z-basis (bit-flip errors) and unfortunately, we can't tell whether they're caused by the eavesdroppers. Therefore, the sending probability has to be reduced to suppress such errors, and consequently, the small sending probability inevitably leads to a lower key rate.

The AOPP method: As the referee highlighted, the AOPP method [*Phys. Rev. A* 101, 042330 (2020)] aims to alleviate this dilemma by introducing active odd-parity pairing through two-way classical communications. The main idea of AOPP is to utilize the low possibility of “both not sending” (defined as V bits), by odd-parity pairing and reject those pairs that have different parity for Alice and Bob (for this information leakage, only one bit of each remaining pair should be used), the remaining pairs would only consist of correct pairs and VD pairs which are errors. Then, by a low possibility of V bits, the error rate is largely suppressed. Therefore, in those experiments employing AOPP enhancement, one typically observes a high bit-flip error rate before AOPP (resulting from the high sending probability) and an extremely low bit-flip error after applying AOPP. Combining the improvement from larger sending probability and additional loss in data postprocessing, the AOPP method typically brings an enhancement in key rate and also extends the maximum communication distance. Since AOPP directly increases the number of detectable events in Z-basis, its improvement in the key rate over the standard SNS-TF-QKD protocol becomes significant in particular at very long communication distances, especially when finite-size effects are taken into account. As the Referee pointed out, this clearly illustrates why AOPP has been widely implemented in QKD systems to improve key rates, particularly in long-distance TF-QKD implementations such as the 1000 km experiment reported in Ref. [20] and many others.

However, in our work, owing to the large data size ($N=10^{12}$), the key-rate curve in Extended Data Fig. 1 shows that the 370-km case has not yet reached the dropping point of the curve; therefore, the advantage arising from the increased number of detectable events in statistical fluctuation effects is not particularly pronounced. Generally speaking, AOPP is not intended to mitigate the increase in bit-flip errors caused by experimental noise, but rather to optimise the inherent deficiencies of the protocol itself.

Note that the key rate achieved in our experiment is comparable to that of the original SNS-TF-QKD protocol when finite-size effects are taken into consideration (see Fig.3 in ref. *Phys. Rev. Applied* 12, 024061 (2019)). If the optimised strategy employing the AOPP were implemented, the key rate would improve by several times, when the communication distance is around 400 km (please refer to Fig.1 in ref. *New J. Phys.* 22 053048 (2020)). However, this enhancement would be much less

pronounced than that achieved in the 1000-km TF-QKD system reported in Ref. [20]. That means, the noise rejection capability afforded by AOPP will become substantially more pronounced when applied to future integrated photonic TF-QKD systems operating over longer distances. There are no fundamental barriers to implementing AOPP, though it requires additional data post-processing overhead. Given the large number of user pairs in our multi-user network—each accumulating a sufficiently large dataset to account for finite-size effects—we opted not to employ this method in this current work. Instead, we focused on characterising and mitigating errors arising from actual experimental noise and system imperfections, that is the factor (2) affecting the experimental key rate at a given distance (please see our response to the Referee's comment 7(d)). Our primary objective in this work is not to pursue ultimate communication distance or key rate, but to demonstrate a scalable and robust hardware platform for integrated quantum networks.

We have added a discussion of noise rejection in this work in [Supplementary Section 4.6](#) (see [Box 10](#)):

Box 10: a new Supplementary Section 4.6:

4.6 Noises rejection and secured key rates

Our primary objective in this work is not to pursue ultimate communication distance or key rate, but to demonstrate a scalable and robust hardware platform for integrated quantum networks. However, to beat the PLOB bound, it's important to carefully address the imperfections in implementing the ideal protocol—in other words, the practical factors that may lead to an increased error rate. Here, we emphasise the optimisations and efforts made in the experiment.

The QBER in Z basis relies heavily on the sending probability theoretically and also relates to the extinction ratio (ER) between send (S) and Not-send (NS). Achieving a sufficiently high ER is important⁴⁷, as it essentially refers to how closely the NS state approaches an ideal vacuum state. From a numerical perspective, if the detectors' response arising from finite ER is far below the dark count rate, the Z basis error rate can be evaluated under the ideal infinite-extinction assumption (a vacuum state is sent), as shown in ref. [79]. Accordingly, when taking the phase estimation period into account, our goal here is to ensure that, during Z basis with the NS state (i.e., transmitting the vacuum state), the detectors' response remains well below the dark-count level (approx. 10 Hz), while within the phase estimation period, the response should approach the detectors' saturation count rate (approx. 2 MHz) to achieve higher counts. This corresponds to an ER of about 60 dB, which is why we emphasise in the manuscript that an ER of at least 60 dB must be achieved between the phase estimation and quantum communication periods. However, from the perspective of a practical protocol implementation, users should not rely on the detector performance to determine their choice of S/NS ER, as the detectors are untrusted and may be fully controlled by Eve. Therefore, it remains essential to maximise the ER to ensure that an ideal vacuum state is transmitted. Under controllable conditions in our lab, the ER can still be evaluated based on the single-photon responses at the server node. According to the measured response rates of the Z basis with S/NS states at the distance of 204 km, the estimated ER reaches over 50 dB in our experiment. Given the current communication distance and detector performance, employing two cascaded IMs (IM I and IM II) to adjust the intensity of the quantum state is already sufficient; therefore, IM III is used independently for pulsation. In fact, all three IMs could be cascaded simultaneously and used jointly for adjusting the quantum state intensity, which would theoretically yield an ER exceeding 90 dB. This means we could leverage an optimised single-photon detector with a dynamic range over 90 dB (e.g., max count rate of 1 MHz and dark count rate of 1 mHz). This capability becomes crucial in very-long-haul quantum communication systems, e.g., in future 1000-km QKD. The high ER and high performance of the photonic chips, as well as precise control over the entire system, have been essential in achieving the reported key rates.

Next, we would like to emphasise the achieved high performance of photonic integrated circuits that enable surpassing the PLOB bound. We have made considerable efforts to ensuring that QKD chips and the full TF-QKD system under well operation to consistently surpass the PLOB bound. These include three aspects:

(1) **Optimising the hardware performance of the integrated quantum photonic chips:** The phase noises of all lasers in the network are minimised. By employing self-injection locking technology, an ultra-low-noise microcomb is generated at the server node to provide the seed light for the user node. Injection locking is used to lock the frequency and phase of the lasers at the user nodes. Moreover, the modulators on the client-node chips adopt a balanced design to achieve a high ER, and multiple modulators can be cascaded to realise a high ER theoretically up to 90 dB. The device bandwidth performance is optimised, and for the phase modulator, the length is designed to balance a lower V_π for ease of driving with adequate modulation bandwidth. All these factors ensure that, at the hardware level, quantum photonic chips can stably support low-noise quantum state generation, low-error-rate quantum state encoding, and operation in high-speed applications.

(2) **Suppressing system noises:** System noises are carefully handled in our chip-based WDM TF-QKD network. Main concerns come from the nonlinear noise photons in the long fibre channels. The SRS noises are carefully rejected by using narrow band, high isolation fibre Bragg gratings and limiting the intensity of strong reference signals. Additionally, the polarisation and time delay drifts have been also monitored to minimise the misalignment. The performance of current configurations and future scalability have been analysed in Supplementary Information Section 4.4.

(3) **Precise phase tracking:** Postselection-based phase tracking has been employed to monitor the phase fluctuations in the long fibre channels, enabling precise reconstruction of the phase difference between remote QKD client-chips. The four-phase method has been implemented to enhance the accuracy of phase estimation (Supplementary Information Section 4.3 and 4.5). Together with low-phase-noise lasers, these techniques enable the generation of highly coherent remote twin fields and reliable single-photon interferences at the server node.

All these above efforts have been made in order to reduce the system noises and enhance encoding accuracy, thereby lowering the error rate and achieving a key rate beyond the PLOB bound under the present experimental conditions. With further optimisation of protocol parameters, advanced data post-processing techniques (such as the AOPP method⁵³), higher-performance single-photon detectors, and ultra-low-loss fibres, TF-QKD networks with longer distance and higher key-rate can be readily upgraded based on the existing framework.

a. An explanation may come from the combination of high extinction ratio (ER) between Send (S) and No-send (NS) states and low sending probability. In Ref 47, Fig.7 indicates that for $ER > 40$ dB, E_z becomes close to P_s . In the present work, the S/NS ER isn't given, but is expected to be high since E_z matches $P_s = 2.4\%$ at 204 km.

b. May the authors confirm the S/NS ER in their work? A minimum ER of 60 dB is reported between phase estimation and quantum communication period, using both IM2 and IM 3, while average individual IM ER is reported to be 33 dB. What is the S/NS ER during the quantum communication period?

Author Reply 7(a-b): We thank the referee for their valuable suggestion and for guiding us to the relevant reference. As the referee pointed out, the QBER in Z-basis relies heavily on the sending probability theoretically and also relates to the ER between S and NS. The discussion in [*Optica* 11, 1385-1390 (2024)] (that is the Ref. 47 in the 1st revised version) implies the importance of achieving a sufficiently high ER, though the results presented in their Fig. 7 are based on the assumption that the dark counts of the detectors are ignored. The sufficiently high ER essentially refers to how closely the NS state approaches an ideal vacuum state. From a numerical perspective, if the detectors' response arising from finite ER is far below the dark count rate, the Z-basis error rate can be evaluated under the ideal infinite-extinction assumption (a vacuum state is sent), as shown in the explicit formula in APPENDIX C of ref. *Phys. Rev. Applied* 12, 024061 (2019). Accordingly, when taking the phase estimation period into account, our goal here is to ensure that, during Z-basis with the NS state (i.e., transmitting the vacuum state), the detectors' response remains well below the dark-count level (approx. 10 Hz), while within the phase estimation period, the response should approach the detectors' saturation count rate (approx. 2 MHz) to achieve higher counts. This corresponds to an ER of about 60 dB, which is why we emphasise in the manuscript that an ER of at least 60 dB must be achieved between the phase estimation and quantum communication periods. However, from the perspective of a practical protocol implementation, users should not rely on the detector performance to determine their choice of S/NS ER, as the detectors are untrusted and may be fully controlled by Eve. Therefore, it remains essential to maximise the ER to ensure that an ideal vacuum state is transmitted. Under controllable conditions in our lab, the ER can still be evaluated based on the single-photon responses at the server node. In response to the referee, according to the measured response rates of the Z-basis with S/NS states at the distance of 204 km, the estimated ER reaches over 50 dB in our experiment.

Given the current communication distance and detector performance, employing two cascaded IMs (IM I and IM II) to adjust the intensity of the quantum state is already sufficient; therefore, IM III is used independently for pulsation. In fact, all three IMs could be cascaded simultaneously and used jointly for adjusting the quantum state intensity, which would theoretically yield an ER exceeding 90 dB. This means we could leverage an optimised single-photon detector with a dynamic range over 90 dB (e.g., max count rate of 1 MHz and dark count rate of 1 mHz). This capability becomes crucial in very-long-haul quantum communication systems, e.g., in future 1000-km QKD.

As the Referee insightfully pointed out, the high ER and high performance of the photonic chips, as well as precise control over the entire system, have been essential in achieving the reported key rates (Please see our response to the Referee's comment 7(d)). Following the Referee's suggestions, we have now added the discussion and clarification of S/NS ER and IM ER in the Supplementary Information Section 4.6 (see Box 10).

c. A low P_s may reduce the rate of successful Z events. Therefore, P_s is generally adjusted as a function of the distance. How did the authors optimize their parameters (P_s , flux, probabilities)?

Author Reply 7(c): In this experiment, we did not separately optimise each parameter for different communication distances. The current set of parameters was obtained via a global optimisation process, starting from reasonable initial values determined by the experimental conditions—such as detector dark count rate and detection efficiency. For instance, the initial sending probability in Z-basis P_s was set to a relatively low value of approximately 2%. The optimisation objective was to surpass the PLOB bound within the 300–400 km distance range. As mentioned previously, our primary focus is not on exhausting all means to achieve higher key rates at longer communication distances, but rather on demonstrating that our integrated quantum photonic chips possess such capabilities. We regard the optimisation of parameters—such as the selection of protocol operating parameters and the refinement of detector dark counts—as improvements that can naturally be incorporated into this system in future work. This allows the present study to concentrate on the client-number scalability aspects of the platform.

d. In any case, overcoming the PLOB without the need of noise rejection routine, is an interesting result that should be explicitly highlighted and commented in the text as an advantage coming from using photonic integrated circuits.

Author Reply 7(d): We thank the referee once again for the suggestion to emphasise how chip-based TF-QKD networks enable surpassing the PLOB bound. We indeed have made considerable efforts to ensure that QKD chips and the full TF-QKD system are operating well to consistently surpass the PLOB bound. These efforts can be categorised into three aspects: (1), optimising the hardware performance of the integrated quantum photonic chips; (2), suppressing system noises; and (3), precise phase tracking. We will discuss in detail as follows:

(1), Optimising the hardware performance of the integrated quantum photonic chips:

The phase noises of all lasers in the network are minimised. By employing self-injection locking technology, an ultra-low-noise microcomb is generated at the server node to provide the seed light for the user nodes. Injection locking is used to lock the frequency and phase of the lasers at the user nodes. Moreover, the modulators on the client chips adopt a balanced design to achieve a high ER, and multiple modulators can be cascaded to realise a high ER theoretically up to 90dB. The device bandwidth performance is optimised, and for the phase modulator, the length is designed to balance a lower V_{π} for ease of driving with adequate modulation bandwidth. All these factors ensure that, at the hardware level, quantum photonic chips can stably support low-noise quantum state generation, low-error-rate quantum state encoding, and operation in high-speed applications. Further, both the client-side TF QKD transmitter InP chips and server-side microcomb SiN chips can be fabricated with foundry-level mass manufacturability and wafer-scale uniformity. **Please see our response to Referee 3's comments.** In the revised manuscript, we have now verified the wafer-scale reproducibility of the server-side Si_3N_4 microcomb chips and clarified the high yield of the client-side InP QKD transmitter chips, which *together* show the QKD network's scalability.

(2), Suppressing system noises:

System noises are carefully handled in our chip-based WDM TF-QKD network. Main concerns come from the nonlinear noise photons in the long fibre channels. The SRS noises are carefully rejected by using narrow-band, high-isolation fibre Bragg gratings and limiting the intensity of strong reference signals. Additionally, the polarisation and time delay drifts have also been monitored to

minimise the misalignment. The performance of current configurations and future scalability has been analysed in Supplementary Information Section 4.4.

(3), Precise phase tracking:

Postselection-based phase tracking has been employed to monitor the phase fluctuations in the long fibre channels, enabling precise reconstruction of the phase difference between remote QKD client-chips. The four-phase method has been implemented to enhance the accuracy of phase estimation (see Supplementary Information Section 4.3 & 4.5). Together with low-phase-noise lasers, these techniques enable the generation of highly coherent remote twin fields and reliable single-photon interferences at the server node.

All the above efforts have been made in order to reduce the system noises and enhance encoding accuracy, thereby lowering the error rate and achieving a key rate beyond the PLOB bound under the present experimental conditions. With further optimisation of protocol parameters, advanced data post-processing techniques (such as AOPP, suggested by the Referee), higher-performance single-photon detectors, and ultra-low-loss fibres (which are not optimisations of the integrated quantum photonic chip itself and are thus not the focus of this work), TF-QKD networks with longer distances and higher key rate can be readily upgraded based on the existing framework. Following the referee's suggestion, we have emphasised in the revised main text (see Box 11) and Section 4.6 (see Box 10) the performance of the integrated photonic chips and the systematic efforts made in this work to surpass the PLOB bound, along with potential improvements in future.

Box 11: revision in main text (page 6&7):

tances, with data collected across all 20 client-chips. Experimental results show QBER_X values of 2.87-3.63% for 204 km and 3.50-4.17% for 370 km. Full experimental data across all 20 client-chips, including gain and Z/X-basis QBER, are summarised in Table S5. The low QBER in the Z/X basis results from a combination of high twin-field coherence, precise quantum state encoding enabled by the integrated photonics, and robust phase tracking across the network.

the communication distances are extended by leveraging ultra-low-noise microcombs and lasers for advanced QKD protocol execution, with prospects for further improvements²⁰. Thirdly, network secu-

Reviewer Comment 8, Two-client chips data:

Although the first experiment didn't meet the criteria of scalability or parallelism, it is still of relevance as it demonstrates wavelength tunability, which is an important feature to enable network reconfigurability. The data have now been moved to the SI (Fig S8 and Table S6), however there is no mention of the experiment neither in the main text nor in the SI sections. The frequency shifter approach is interesting, however wavelength tunability should be also listed as a potential way to connect different clients for a fully connected network.

Author Reply 8: We sincerely thank the Referee for their constructive suggestions. We fully agree that the wavelength tunability of the integrated user nodes is also an important feature for building large-scale multi-user networks. Limited information was provided in Supplementary Information Section 4.1 of the manuscript after 1st round revision. Following the referee's suggestion, we have now included a more detailed description of the experiment shown in Fig. S11 and Tab. S6 with an independent Supplementary Information Section 5.3, and added the reference in revised main text (see Box 12).

Box 12: added text in Conclusion (page 7):

ability and reliability of the quantum networking chips. Finally, our integrated quantum photonic devices and technologies can be readily extended to field-deployable QKD networks with practical configurations. These include implementing asymmetric networks by further reducing low-frequency noise in the microcomb lasers, and establishing fully-connected or reconfigurable networks by combining server-side quantum frequency conversion (see Supplementary Section 5) with the demonstrated client-side wavelength tunability (see results in Fig.S11 and Table S6).

a new Supplementary Information Section 5.3:**5.3 Wavelength tunability of the integrated QKD client chips**

From the perspective of developing an integrated quantum photonic chip platform compatible with a truly large-scale WDM-based network architecture, two aspects are of particular importance: 1), The feasibility of mass-manufacturing integrated QKD client chips with uniform performance through cost-efficient fabrication processes, while maintaining high-fidelity specifications for advanced QKD protocols; 2), The capability of generalised device architectures to accommodate diverse protocol requirements across multiple users (e.g., reconfigurability for WDM network implementations). In the main text, we have placed particular emphasis on the first aspect, and shown the scalability of the integrated quantum photonic devices. Regarding the second aspect, we have briefly discussed the tunability of the on-chip lasers and their full-range injection locking capability in Fig.2j. To further verify the versatility of our integrated client chips, we employed a pair of QKD client chips and tuned the on-chip laser wavelengths to perform SNS-TF-QKD protocols at different wavelengths. This test effectively demonstrates that, within the WDM framework, one InP chip can still be employed without the need for wavelength-specific adjustments, thereby greatly enhancing practicality. Figure S11 and Tab. S6 report two QKD client-chips but with 10 distinct wavelength-configurations for quantum signals (λ'_1 through λ'_{10}), to demonstrate the operational flexibility of our generic QKD chips in reconfigurable quantum networks. The experimental conditions are essentially consistent with those described in the main text, except that: in each test round, only the selected wavelengths of quantum and reference signals were running, without considering parallel operation of all wavelength channels; and were all kept in the short downstream fibre configuration.

Reviewer Comment 9: *How much channel asymmetry can be tolerated with the 60 Hz linewidth?*

Author Reply 9: The tolerance to channel asymmetry depends on the noise performance of the lasers across the entire frequency range, as we explained in our response to the 1st round review (please see Supplementary Information Section 5.2). From the perspective of the frequency-noise power spectral density, the instantaneous 60 Hz linewidth represents the laser's broadband background noise (that is the white noise), which then defines the lower bound of its linewidth performance and correspondingly the upper bound of the tolerable channel asymmetry. Thus, in theory, the system's maximum tolerance to the optical path difference—namely, the coherence length in fibre—is given by: $2 * 10^8 \text{ m/s} * 1/(60 \text{ Hz}) = 3333 \text{ km}$. However, as the asymmetry becomes more pronounced, the *low-frequency* components of frequency noise start to play a significant role and the influence of the integrated linewidth begins to manifest itself, which introduces a low-frequency fluctuation superimposed on the interference outcome. Such relatively low-frequency fluctuations can be detected and successfully tracked through data post-processing (see *Phys. Rev. Lett.* 130, 250802 (2023)), or alternatively, suppressed by auxiliary techniques that reduce low-frequency noise, thereby allowing the laser to approach the white-noise limit even in the low-frequency regime (see Supplementary Information section 5.2). However, an ultra-narrow instantaneous linewidth still remains critically important, as it ensures that, for relatively small asymmetry, the laser phase noise can be almost neglected. In contrast, lasers with a large instantaneous linewidth exhibit high noise across the full frequency range, imposing extremely stringent requirements on optical path matching and making long-distance optical-field interference nearly impossible.

Reviewer Comment 10: *A recent publication demonstrated a microcomb chip to implement WDM MDI-QKD network [Yan W. et al. npj Quantum Inf 11, 97 (2025)]. Although the microcomb lines are much broader than in the present work, a brief mention might be useful to include in the literature review.*

Author Reply 10: We thank the referee for bringing to our attention the recent MDI-QKD study that utilises a microcomb source, and we have updated the discussion of this work in the main text.

Box 13: revision in main text (page 4):

Integrated ultra-low-noise microcombs and QKD client chips

The advancement of integrated quantum photonic technologies has sparked significant interest in high-speed, cost-effective, miniature, and readily manufacturable devices for quantum communications, with the specific emphasis on practical QKD applications³². Previously, protocols of prepare-and-measure QKD^{33–39}, MDI-QKD^{40–43}, and entanglement-based QKD^{14,44–46} have been implemented with integrated photonic devices, but primarily in the point-to-point scenario. Notably, chip-based point-to-point TF-QKD has been demonstrated using partially integrated InP photonic chips⁴⁷, and recent work shows the potential of microcombs in MDI-QKD networks⁴⁸.

Reviewer Comment 11: *Caption 2j, 2k: the measurements refer to the output intensity of the IMs not the EOPMs.*

Author Reply 11: We thank the Referee for their meticulous review, and we have corrected the erroneous statement accordingly.

We would like to express our sincere gratitude once again for the Referee's comprehensive and insightful assessment of our manuscript. Their thoughtful comments on readability, experimental presentation, and protocol security have been invaluable in further improving the quality of our work.

Referee #2 (Remarks to the Author):

Reading the new version of the paper and the very detailed reply to all the referees, we are really impressed by the amount of new experimental realizations and data acquired in so few weeks by Zheng et al. They have reimplemented the whole TF-QKD network, including twenty TF-QKD chips and have recollected all experimental data. The realization of pairwise QKD across twenty client-chips through ten wavelength-multiplexed channels, together with the clarification of some ambiguous details in the main and in supplementary sections, made this paper a very high level technical paper that bring significant advancement in the field of quantum communication.

Even if at proof-of-principle level, it represents for sure a technical advancement towards TF-QKD implementation, approaching a real scenario, where a scalable TF-QKD network could be achieved. As pointed out by the authors in their reply, the use of integrated quantum photonics and chip-scale miniaturization represents a fundamental step for a cost-effective scalable WDM TF-QKD architecture.

Since the results obtained by the authors, although remarkable, are still, in our opinion, too technical and specialistic for a journal as Nature, publication in a journal such as Nature Photonics or Nature Physics would place the paper within the appropriate reference community without in any way diminishing its scientific value.

We sincerely thank the Referee for their extremely valuable comments and suggestions, and for recognising our work as a high-level technical contribution that brings significant advancement to quantum communication. Following the Referee's suggestions and comments in the first revision, we have now implemented the whole TF-QKD network with 20 physical QKD client-chips through ten wavelength channels and also incorporated tests with symmetric long-haul fibres. We fully agree with the Referee that these enhancements have substantially strengthened the demonstration of our network's capabilities. We are grateful for their acknowledgement of the newly implemented experiments and revisions in the first resubmission, which have clarified the experimental scale and demonstrated the network's scalability. In this second revision, we have now included further experimental data and clarifications to better substantiate our scalability claims, thereby providing additional evidence of the manufacturability and system-level scalability of both the client-side InP QKD transmitter chips and the server-side SiN microcomb chips.

Following the Referee's suggestion, the manuscript has been revised to balance broad accessibility with specialist rigour, making it more suitable for the diverse readership of *Nature*. In particular, the Abstract and Introduction have been refined to emphasise the scalability and cross-disciplinary relevance of our work. We believe that all concerns raised by the Referee have been fully addressed, and their insightful feedback has greatly improved the overall quality of the manuscript.

Referee #3 (Remarks to the Author):

To the Authors, Thank you for the extensive and impressive revisions to the manuscript and for your detailed response letter. The re-implementation of the experiment with 20 physical QKD chips and the inclusion of tests with symmetric long-haul fibers have substantially strengthened the work and addressed many of my initial concerns.

While the manuscript is much improved, I believe further clarification on a few points related to manufacturability and system-level scalability would significantly enhance the impact of your claims.

We sincerely thank the Referee for their insightful and constructive comments on our manuscript. We agree that re-implementing the experiment with 20 physical QKD chips and incorporating tests with symmetric long-haul fibres has significantly strengthened our network work. We appreciate the Referee's recognition of all these revisions and the newly conducted experiments. We also thank the Referee for their valuable suggestions on manufacturability and system-level scalability of the client-side InP QKD transmitter chips and server-side SiN comb chips. In the revised manuscript, we have now included additional characterisation data and provided further clarifications to better support our claims in these aspects. We believe that addressing the manufacturability and scalability of client-side chips and server-side chips can indeed significantly enhance the impact of our work.

Reviewer Comment 1: Overall Yield and Selection of Client-Side InP Chips:

The reported 97.5% yield for the electro-optic modulators is a strong indicator of the fabrication quality. However, this is a metric for a single component type. The overall yield of a fully functional QKD transmitter chip—where all lasers, modulators, and attenuators must work to specification—is a more critical metric for assessing mass-manufacturability.

Could you please clarify the wafer-level yield of fully operational InP QKD chips that passed all performance criteria? To provide context, could you state whether the 20 chips used in the experiment represent the total number of chips fabricated, or if they were selected from a larger pool after other devices were discarded due to performance issues?

Author Reply 1: We thank the Referee for raising this important point regarding the overall yield of a fully functional QKD transmitter chip. We fully agree with the Referee that the overall yield of a fully functional QKD chip is a more critical metric, and indeed we have to use the overall yield to characterise those QKD InP chips. The key components for a QKD transmitter include the lasers, phase/intensity modulators, and optical attenuators, which have been monolithically integrated on InP chips. Phase/intensity modulators and optical attenuators are constructed by electro-optic phase modulators (EOPMs), together with Mach-Zehnder interferometers. In the first-resubmitted version, we have tested all lasers and EOPMs in the 20 copies of InP chips.

As shown in the Figs. 2j, 2k, the power spectral density and spectral characteristics of the injection-locked lasers confirm that all client-side lasers can meet the stringent requirements of TF-QKD. The tunability of injection-locked laser has also been shown in Fig.2j. In the first-resubmitted version, we did not statistically express the results in terms of yield; however, all lasers on the 20 InP chips indeed work successfully with ultra-low noises for TF QKD. That means the laser yield is 100% on the 20 tested chips.

As shown in the Figs. 2i, we have characterised all EOPMs and achieved a yield of 97.5% across all 20 InP chips (117 out of 120 EOPMs), with only three EOPMs failures. Since each transmitter chip

contains multiple EOPMs and our design supports flexible configuration, even in the rare case of a single EOPM failure, the chip can still implement the full TF-QKD protocol—by using a single-drive scheme as an alternative to the dual-drive push-pull configuration. This adaptability ensured full operational capability across all 20 InP chips in the QKD network. We had clarified how the full TF-QKD network is implemented by driving the EOPMs in [Supplementary Section 4.1](#) Experimental setup “Quantum keys encoding at the InP client chips” in our first resubmitted version. Additionally, we have performed bandwidth measurement in the [Supplementary Fig.S7](#) to further substantiate device performance and reproducibility.

Given the 100% yield of the lasers and the 97.5% yield of the EOPMs across the twenty chips, we conclude a high overall system yield, and all twenty chips functioned properly. In response to the Referee’s suggestion, we have now clarified in the revised manuscript that the high overall yield of the fully functional QKD transmitter chips (see [Box 1](#)).

Box 1: new text in revised main text (page 4):

mode suppression in Fig.2j. The lasers all operated properly, and the EOPMs exhibited a high yield of 97.5%, while the adaptable circuit design ensures that the TF-QKD protocol remains fully executable ([Supplementary Information 4](#)), enabling all twenty randomly selected client chips to function properly in the network. These results also show the capability of massive integration and identical operation of low-noise lasers for scalable WDM-based TF-QKD networks.

Regarding the chips we have characterised, all the 20 InP chips used in this work were taken from 10 different dies on a single foundry-processed 3-inch wafer. Specifically, we receive 12 dies from the foundry, each containing 2 independent QKD user transmitter circuits. A total of 24 functional QKD copies were available after cleaving. We randomly selected 20 chips for packaging and testing (every two InP chips are packaged on the same PCB for testing, as we have clarified in [Fig.1c](#))—without any special pre-selection. This approach validates the foundry-level manufacturability and scalability of our design. In the revised manuscript, we have added clarifications in the caption of [Fig.1c](#) and [Supplementary Information Section 4.1](#) (see [Box 2](#)).

We sincerely thank the Referee for this valuable comment, which has helped us more accurately assess and present the mass-manufacturability and overall yield of the QKD InP transmitter chip.

Box 2: new sentence in the caption of Fig.1c

Figure 1 An integrated-photonic TF-QKD network system. (a), Schematic diagram for a many-user long-haul TF-QKD WDM-based star network system. This network could support a large number of QKD clients (N) and long client-to-client communication distances (L). It can mitigate detector vulnerabilities at the central (untrusted) server node, while enabling cost-efficient resource sharing among many legitimate QKD users. (b), Conceptual diagram of large-scale integrated-photonic TF-QKD network, “Weiming Quantum Chip-Network”, with both large N and long L . QKD client chips integrate local lasers, PMs, IMs and VOAs, delivering high-speed operation, full integration, cost-effectiveness, miniaturisation and mass-manufacturability for TF-QKD network. The server chips encompass an integrated microcomb, as well as linear-optic circuit (LOC, including optical switches, wavelength multiplexers, and beam splitters) modules, single-photon electro-optic frequency shifters (EOFSs), SNSPD modules, and electronic logics. The integrated microcomb provides a broad spectrum of ultra-low-noise coherent Hz-level-comb-lines for TF-QKD, enabling WDM-based networks with inherent phase-coherence between QKD client chips. Microcomb and client chips are clock synchronised within the network, with the microcomb driving many chip-based transmitters to reliably share quantum secure keys across long-haul fibre channels. (c), Photograph of integrated-photonic quantum chips used in our network, including an integrated Si_3N_4 microcomb chip (unpacked) at the centre, and 20 copies of identical InP QKD client-chips (two InP chips are packaged on one printed circuit board). Both server-side microcomb chips and client-side QKD transmitter chips can be massively manufactured with wafer-scale reproducibility. These 20 InP QKD chips used in this experiment were randomly selected from a set of 24 copies fabricated on a 3-inch wafer, without any pre-selection.

new text in Supplementary Information Section 4.1:

Quantum keys encoding at the InP client chips: The InP client chips were electrically packaged on a PCB (two chips per board) to ensure stable loading of multi-channel RF signals. We mark that in the TF networking implementation, the two InP chips of the same client pair were always tested on physically separated nodes. The InP chips were coupled via optical fibres mounted on translation stages. As illustrated in [Fig.2a](#) and implemented in [Fig.2h](#), each InP chip was accessed using three single-mode fibres: one for reference seed (signal) input/output, and two for quantum seed (signal) input/output. The coupling loss between chip and fibre vary between different samples, but the typical value is around 4 dB per facet. For future large-scale deployment, standard fibre-array packaging can be adopted to enhance operational stability and user accessibility. Laser diode controllers were used to control the SOA section of on-chip DBR lasers and the chip’s temperature,

new text in revised main text (page 4):

We first characterise all lasers and modulators on these 20 QKD chips (randomly selected from a 3-inch wafer) to demonstrate their reproducibility, performance and uniformity. It shows that 117 of

Reviewer Comment 2: Scalability of the Server-Side Si₃N₄ Microcomb Fabrication:

The manuscript highlights that the scalable InP client chips were fabricated at a commercial foundry (Smart Photonics), which strongly supports claims of reproducibility. In contrast, the "Authors Contributions" section and supplementary details suggest the critical server-side Si₃N₄ microcomb was fabricated in-house at the university. This distinction is important for evaluating the end-to-end scalability of the network architecture.

Could you please comment on the scalability and reproducibility of this in-house Si₃N₄ fabrication process? Is the manufacturing of the microcomb itself a potential bottleneck for the large-scale deployment of this network architecture, and how does its fabrication yield and performance uniformity compare to the commercial foundry process used for the client chips?

Author Reply 2: We fully agree with the Referee that the performance of both the client-side InP QKD transmit chips and the server-side Si₃N₄ microcomb chips is essential to support the claims of reproducibility and scalability for the entire TF-QKD networks. The client-side InP QKD chips were fabricated at a foundry (see discussion and clarification of QKD chips in Boxes 1, 2).

For the server-side Si₃N₄ microcomb chips, while the original device was fabricated in a university facility, we have now verified the low-loss Si₃N₄ devices fabricated by a commercial foundry, using the same fabrication processes. The chip was fabricated on a 4-inch Si₃N₄ wafer with processes compatible with large-scale manufacturing, and its reliability has been confirmed. To demonstrate device uniformity, we have implemented new measurements of the Q factors of microresonators from different dies on the same Si₃N₄ wafer. These wafer-scale microresonators exhibit comparable ultra-high Q factors—a key metric for microcomb reproducibility—to the device used in TF-QKD network. Moreover, the foundry-fabricated devices with high Q factors also ensured robust comb generation with low noise (see new results in Fig.S3). **This confirms that the low-noise light source at the server chip also exhibits strong reproducibility and wafer-scale scalability.** Therefore, a Si₃N₄ microcomb chip can support a large number of QKD client chips (as demonstrated in the main text and discussed in Conclusion), and the network can be scaled up using such wafer-scale microcomb chips. We have included a more detailed discussion on the fabrication and characterisation of the Si₃N₄ devices in **Supplementary Information Section 1**, new Fig. S1, Fig. S3, and the main text to emphasise the wafer-scale reproducibility of the Si₃N₄ chips (see Box 3).

Box 3: new paragraphs in Supplementary Section 1**1 Fabrication and characterisation of integrated microcomb and QKD transmitter chips**

Integrated-optical Si₃N₄ microcomb chips: The integrated optical ultra-high-quality (Q) microresonator and microcomb devices were fabricated using the following processes, as shown in Fig.S1a. Firstly, a silicon wafer with a 10 μm-thick thermal (SiO₂) top layer was deposited by a 100 nm-thick Si₃N₄ layer using low-pressure chemical vapour deposition (LPCVD). The waveguides were patterned by deep-UV lithography and fully etched by inductively coupled plasma (ICP) processes. The chip was up-cladded with a layer of 2 μm-thick SiO₂ by LPCVD. An annealing process at 1150 °C was then applied for stress relief. The wafer was finally diced into chips and facet-polished for improving coupling efficiency. We adopted the same processes to fabricate ultra-low-loss Si₃N₄ devices using both university and commercial foundry facilities. Figure S1b shows a photograph of a foundry-fabricated 4-inch Si₃N₄ wafer.

Both university-fabricated (Fig.2 and Fig.S2) and foundry-fabricated (Fig.S3) Si₃N₄ devices demonstrate similar performance. The wafer-scale fabrication process for ultra-low-loss Si₃N₄ devices has been extensively demonstrated in previous studies [66–69]. To evaluate fabrication uniformity, we here conducted wafer-scale testing of Si₃N₄ devices fabricated at a commercial foundry. Microresonators on several different dies from the same wafer were characterised. The measured transmission spectra of the microresonators near 1550 nm are shown in Fig.S3a, and the wavelength-dependent intrinsic Q factors are plotted in Fig.S3b. Each column in Fig.S3a,b represents data obtained from a microresonator on a different die with slightly varied designs. The extracted intrinsic Q factors near 1550 nm are approximately 51.6 million, 44.4 million, and 56.4 million for the three devices, respectively. Averaged over the 1510–1630 nm wavelength range, the intrinsic Q factors are 53.1 million, 42.8 million, and 45.6 million—approximately double those of university-fabricated devices (Fig.2 and Fig.S2) using the same process. The measured Q factors are sufficiently high to support robust self-injection-locked Kerr frequency comb generation [70, 71]. Among these chips, the Chip II in Fig.S3 was designed to operate under critical coupling; therefore, we characterised its optical comb generation performance. Under normal dispersion conditions (Fig.S3c), a self-injection-locked comb was obtained (Fig.S3d), exhibiting exceptionally low frequency noise (Fig.S3e) with a white-noise floor around 5 Hz²Hz^{−1}. Although the Fig.2 devices directly used in the quantum network experiments exhibit a lower intrinsic Q factor than the foundry-fabricated samples, they still enable stable and efficient microcomb generation. These results confirm that the low-noise light source at the server chip also exhibits strong reproducibility and wafer-scale scalability. Thus, a single Si₃N₄ microcomb chip can support a large number of QKD client chips (as demonstrated in the main text and discussed in Conclusion), and the network can be scaled up further using such wafer-scale microcomb chips.

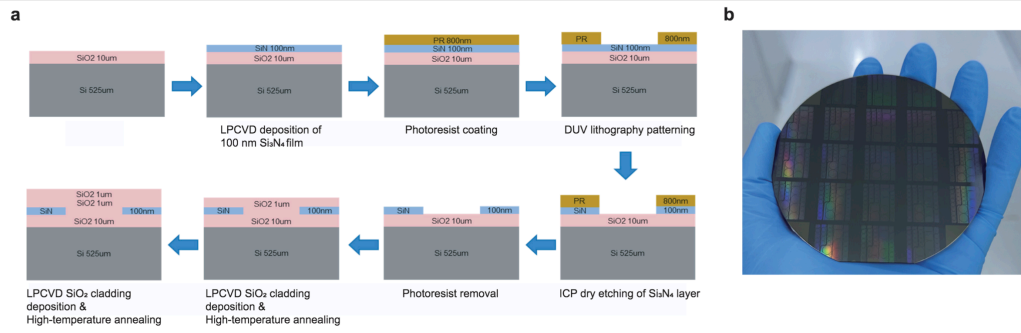
Box 3: a new Figure S1 in Supplementary Information:

Figure S1 Wafer-scale fabrication of Si_3N_4 devices. (a), Schematic of the fabrication process flow. (b), Photograph of a fabricated 4-inch Si_3N_4 wafer.

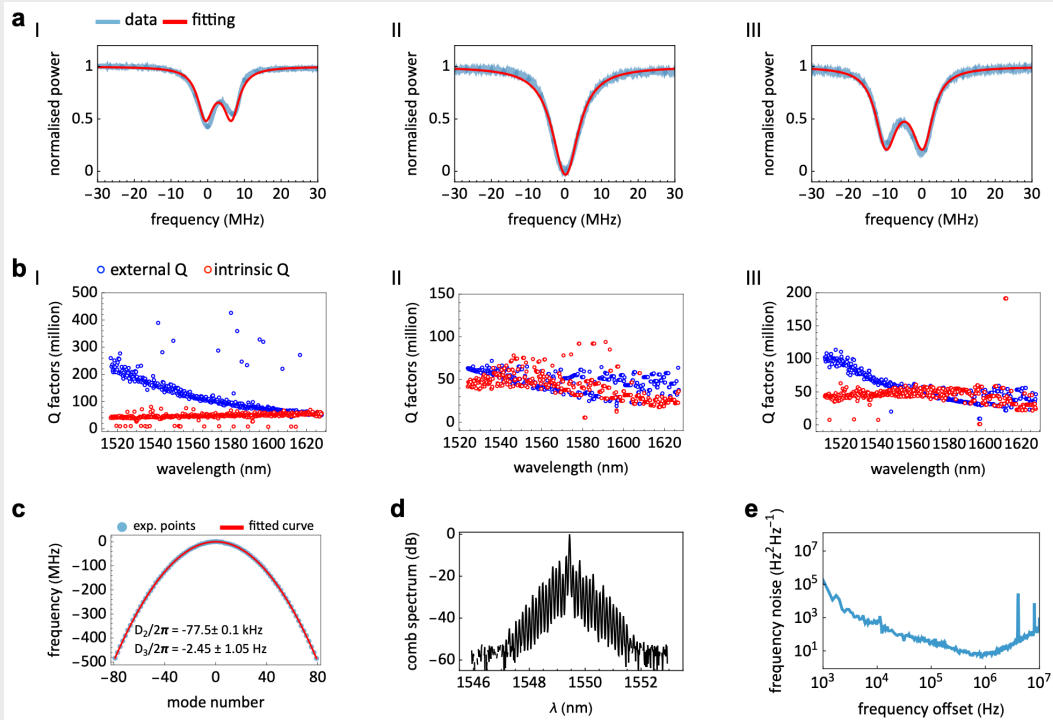
a new Figure S3 in Supplementary Information:

Figure S3 Wafer-scale characterisations of foundry-fabricated Si_3N_4 microresonator and microcombs from different dies on the same wafer. Each column represents data obtained from a microresonator on a different die (Chip I, II, III) with slightly varied designs. (a), Measured normalised transmission spectra and fitted Q factors near 1550 nm for microresonators from three different dies on the same 4-inch Si_3N_4 wafer. Intrinsic Q factors of each resonator are 51.6 million, 44.4 million, and 56.4 million. The blue markers represent the measured transmission and the red curves show their corresponding Lorentzian fits. (b), Wavelength-dependent intrinsic (blue) and loaded (red) Q factors of the three microresonators within the 1510–1630 nm range. The average intrinsic Q factors for the three devices are 53.1 million, 42.8 million, and 45.6 million. Chip II exhibits critical coupling, thus we measured its (c), dispersion data, (d), self-injection locked optical comb spectrum, and (e) frequency noise spectrum, with a white-noise floor around $5 \text{ Hz}^2\text{Hz}^{-1}$. These results show even higher intrinsic Q factor than the university-fabricated samples, and confirm that the low-noise light source at the server chip also exhibits strong reproducibility and wafer-scale scalability.

new text in revised main text (page 4):

sive wavelength-multiplexed QKD between a large number of client chips (currently we adopted a 30-GHz spacing for proof-of-concept demonstration). **iii, high-yield fabrication and operation of fully functional QKD transmitter chips ensuring high performance, along with the wafer-scale reproducibility of microcomb chips, critically advance the scalability and reliability of quantum networks.**

spectral range (FSR) was measured to be 30.03 GHz. Fabrication and characterization details for the **wafer-scale microresonators** are provided in Supplementary Information 1, exhibiting consistently high Q factors and well-controlled dispersion. By adjusting the air gap

Addressing these points would provide a more complete picture of the practical path toward large-scale deployment, directly supporting the manuscript's central theme of scalability.

We fully agree with the Referee that the core contribution of this work lies in demonstrating a long-haul, multi-client TF-QKD network using integrated photonic chips that offer high scalability and manufacturability. In direct response to the Referee's comments, we have now verified the wafer-scale reproducibility of the server-side Si_3N_4 microcomb chips and clarified the high yield of the client-side InP QKD transmitter chips, *together* substantially strengthening our claims regarding the QKD network's scalability. We believe that these revisions significantly enhance the impact of our work by underscoring the transformative potential of integrated photonics in enabling large-scale, practical quantum communication networks. Accordingly, we have revised the **Abstract and Introduction** to better emphasise the demonstrated scalability and manufacturability of both the client-side InP transmitter chips and the server-side Si_3N_4 microcomb chips (see **Box 4**). Once again, we sincerely thank the Referee for their highly insightful and constructive feedback.

Box 4: rephrased abstract

Quantum key distribution (QKD) leverages the principles of quantum mechanics to enable provably secure communication^{1,2}. One significant challenge persists in the development of large-scale QKD networks with a large number of clients over long communication-distances^{3,4}. While quantum relays continue to pose practical difficulties⁵, existing trusted node networks^{6–10}, point-to-multipoint networks^{11,12}, and wavelength-multiplexed entanglement networks^{13,14}, encounter issues such as reliance on trusted intermediaries or limited distances. Twin-field (TF)-QKD provides a compelling architecture that can overcome those issues while enhancing communication-distance¹⁵. Though long-distance point-to-point TF-QKD have been achieved^{16–22}, realising large-scale network requires scalable quantum devices. Here, we report proof-of-principle demonstration of an integrated-photonic TF-QKD network with exceptional scalability and reliability. This network includes twenty independent client-side QKD transmitter chips with one server-side optical microcomb chip. The microcomb generates a broad spectrum of ultra-low-noise coherent frequency combs with Hertz-level linewidths, which serve as seeds and references for all client-chips. Each client-chip regenerates ultra-low-noise light phase-locked to microcombs and prepares quantum keys through monolithic integration of all components. We sequentially implement pairwise QKD across twenty client-chips through ten wavelength-multiplexed channels, with each surpassing the repeaterless bound at 370 kilometres in spooled fibre, achieving a networking capability (client-pairs $\times$ communication-distance) of 3,700 kilometres. **We further demonstrate the wafer-scale reproducibility of both server-side microcomb chips and client-side QKD transmitter chips, together establishing the system-level scalability.** Combining mass-manufacturability, cost-effectiveness and high scalability of integrated photonics with long-distance quantum communication represents a viable path to large-scale quantum networks.

rephrased introduction

Here, we present proof-of-principle laboratory demonstration of user-massively-scalable and long-haul TF-QKD network enabled by integrated photonics, named as "*Weiming Quantum Chip-Network*". Our integrated-photonic QKD network comprises a central server chip that integrates an optical microresonator frequency comb (microcomb) on silicon nitride (Si_3N_4) platform, and 20 copies of independent client-side QKD transmitter chips that monolithically integrate all essential components for key preparation based on indium phosphide (InP) photonic circuits. **These client-side QKD chips fabricated on a 3-inch InP wafer and server-side microcomb chips fabri-**

cated on a 4-inch Si_3N_4 wafer both demonstrated high performance, reproducibility, and operational yield, thus providing scalable quantum devices for network implementations. We harness integrated microcomb technology, which has revolutionised classical photon-

rephrased conclusion

span a vast quantum network system with large N and long L . **Combining the demonstrated wafer-scale reproducibility of client-side and server-side chips** with advanced heterogeneous integration, this

Referee #4 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

We sincerely thank the Referee for their extremely valuable comments and suggestions, which have been instrumental in refining and improving our work. We are grateful for their recognition of the newly implemented experiments and revisions in the first resubmitted manuscript, which have clarified the true scale of the experiments and demonstrated the network's scalability, as suggested by the Referee in the first review process. We appreciate the referees' insightful comments and suggestions on scalability, security, and experimental details, pointed out in the second review. In the revised manuscript, we have added new experimental data and provided further clarifications to support our claims. The manuscript has been revised to better balance the broad accessibility and specialist rigour. In particular, the Abstract and Introduction have been rephrased to emphasise the scalability and cross-disciplinary relevance of our work for a broad readership. We believe that all the referee concerns have been fully addressed, and their constructive feedback has significantly enhanced the overall quality of the manuscript.

Referee #1 (Remarks to the Author):

Please find below the review of the revised Nature Manuscript ID: 2024-10-21482 entitled “Large scale Quantum Communication Networks with Integrated Photonics”, by Professor Wang and coauthors. I have now reviewed the comprehensive response of the authors and the new manuscript. I am pleased to see that, in their response and the new manuscript version, the authors have lifted all risks of experimental misinterpretation and significantly improved the readability of the manuscript:

- The wafer-scale reproducibility for TF-QKD chips and their reliability in terms of fabrication and performance is a strong message which is now highlighted in the abstract and introduction. The conclusion was improved by the addition of fair considerations on potential limitations of the experimental conditions and prospect of practical deployment.*
- The organization of new Figure 2 significantly improved clarity and accessibility.*
- Likewise, SI 4.1 and Figure S5 now lift critical ambiguities and clearly demonstrate the scalability of the experimental setup.*
- An important comment was raised regarding the phase encoding, namely the risk that the encoded X-basis state may have been matched in phase. The authors have now fully addressed this concern in SI 4.2. and Figure S7. SI 4.6 further describes the authors efforts in minimizing sources of noise and errors to consistently overcome the PLOB without the need of additional noise rejection routine.*

I believe that, in its present shape, the manuscript will meet the expectations of expert readers while maintaining a sufficiently accessible message to reach a broad readership. The scalability achieved for such a challenging experiment, and the extensive set of data presented in the manuscript and supplementary material, are likely to strongly impact both the photonic integration and the quantum communications communities. I am therefore pleased to recommend publication of the manuscript in Nature, and I take the opportunity to congratulate the authors for their considerable work and efforts.

We sincerely thank the Referee for their patience and careful assessment throughout the multiple rounds of review, and for their constructive and insightful comments on the scalability, security, and experimental details of our work. Their thoughtful feedback and guidance have been very instrumental in improving the clarity and overall quality of the manuscript.

Referee #3 (Remarks to the Author):

The authors have satisfactorily addressed all my previous concerns and comments. The manuscript has been improved significantly and I believe it is now ready for publication. Therefore, I can recommend the publication in Nature.

We would like to thank the Referee for their sustained rigor and thoughtful guidance throughout the review process. Their comments have been instrumental in helping us to refine the manuscript and improve the overall quality of the work, and suggestions have been invaluable in strengthening the final version.

Please find below the review of the revised Nature Manuscript ID: 2024-10-21482 entitled “Large scale Quantum Communication Networks with Integrated Photonics”, by Professor Wang and coauthors. I have now reviewed the comprehensive response of the authors and the new manuscript. I am pleased to see that, in their response and the new manuscript version, the authors have lifted all risks of experimental misinterpretation and significantly improved the readability of the manuscript.

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