
Supplementary information

**Large-scale quantum communication
networks with integrated photonics**

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Supplementary Information:

Large-scale Quantum Communication Networks with Integrated Photonics

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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.

We first characterise the Q values and dispersion of the university-fabricated microresonator, which are key parameters for the generation of dark-pulse combs. A wavelength-tunable laser output was split into three paths that simultaneously probed: (1) the Si₃N₄ microresonator, (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.S2a, and (3) a fibre asymmetric Mach-Zehnder interferometer (MZI) providing fine frequency resolution. Through scanning the laser wavelength around 1550 nm and comparing the transmission spectra, we obtained a corrected microresonator transmission spectrum (Fig.S2b) from which the dispersion relation (Fig.S2c) was extracted. The whispering-gallery modes (WGMs) of the microresonator can be described by expanding the angular frequency as:

$$\omega_\mu = \omega_0 + D_1\mu + D_2\mu^2 + D_3\mu^3 + \dots \quad (\text{S1})$$

Spanning around mode 0 (centred at 1549.78 nm), the linear dispersion (free spectral range, FSR) of the microresonator was measured to be $D_1/(2\pi) = 30.034 \pm 0.007$ GHz and higher-order dispersion $D_2/(2\pi) = -0.309 \pm 0.001$ MHz, $D_3/(2\pi) = 0.733 \pm 0.003$ kHz, indicating a normal dispersion.

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 [27, 64–66]. 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 [26, 67]. 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-

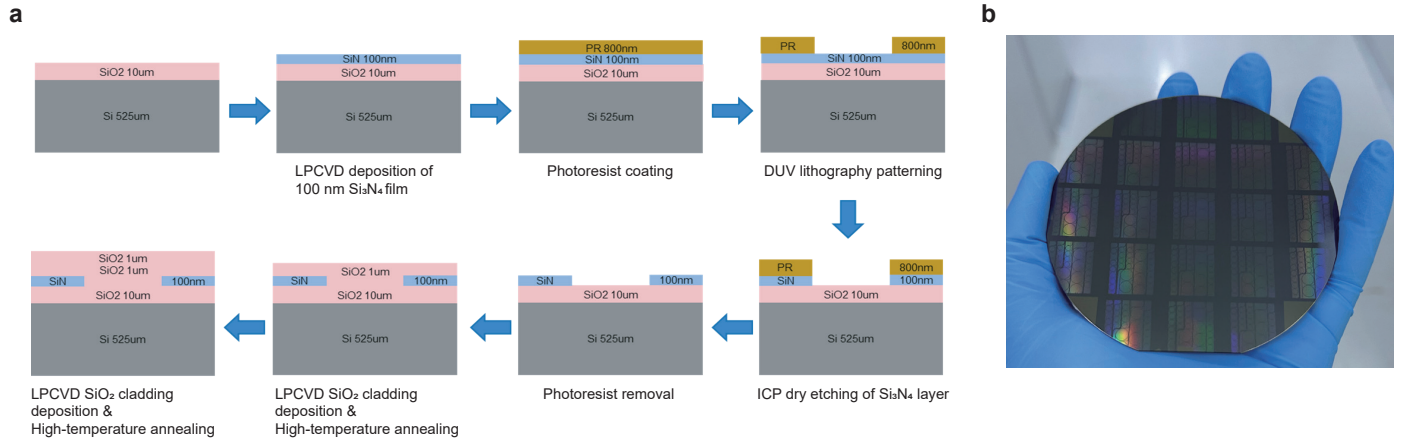


Figure S1 Wafer-scale fabrication of Si_3N_4 devices. (a), Schematic of the fabrication process flow. (b), Photograph of a fabricated 4-inch Si_3N_4 wafer.

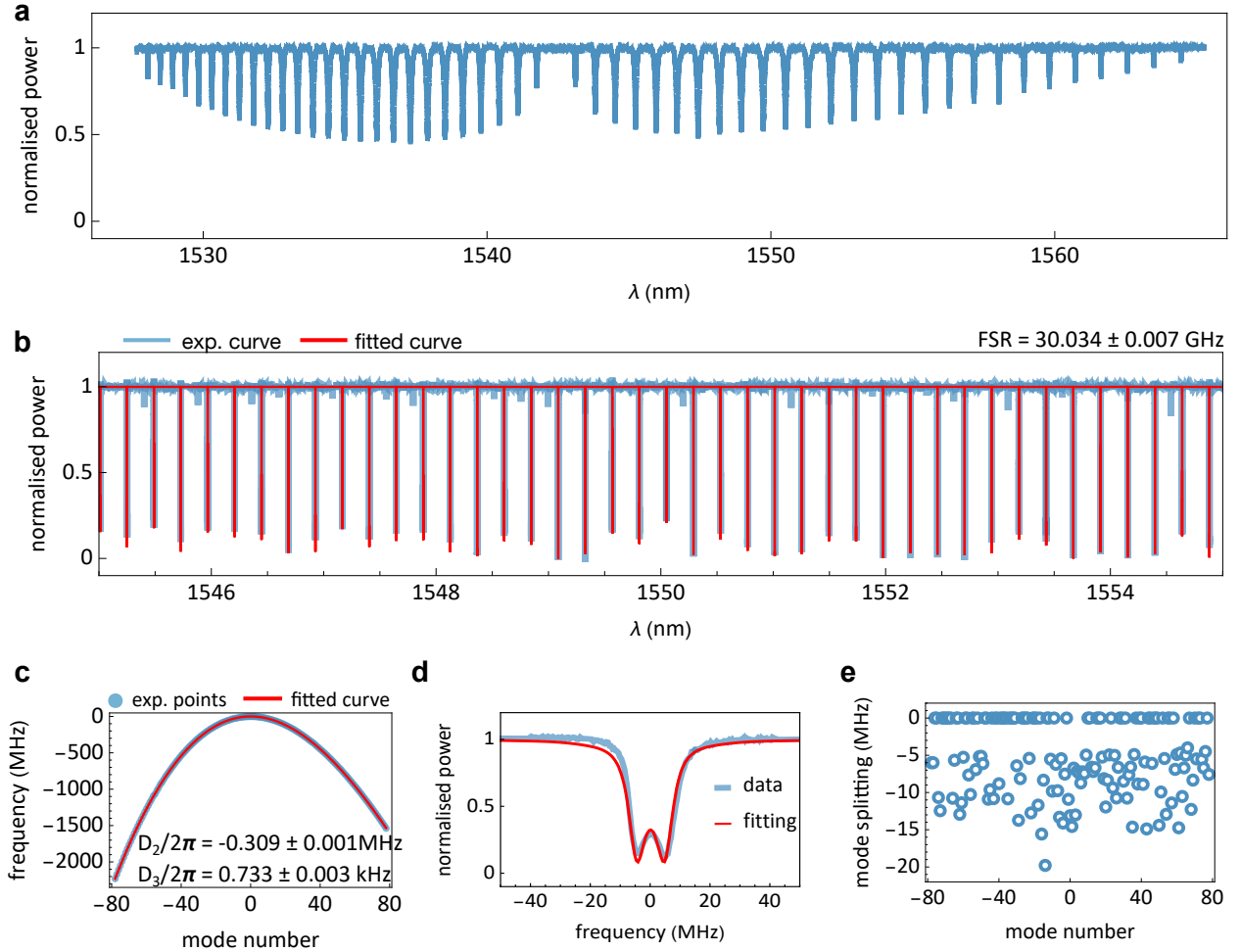


Figure S2 Calibration of the university-fabricated Si_3N_4 microresonator and microcombs. (a) and (b), Measured transmission spectra of the HCN gas cell and microresonator. In (b), experimental results are fitted with a multi-peak Lorentzian pattern. (c), Dispersion calibration of the microresonator. The integrated dispersion is plotted, defined as $D_{\text{int}} = \omega_{\mu} - \omega_0 - D_1\mu$, where μ denotes mode number relative to centre mode at 1549.78 nm. $D_1/2\pi$ is the FSR around mode 0, which is estimated to be 30.034 ± 0.007 GHz. Higher order dispersion is extracted to be $D_2/(2\pi) = -0.309 \pm 0.001$ MHz, $D_3/(2\pi) = 0.733 \pm 0.003$ kHz. (d), 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 WGMs. (e), Splitting distance of the modes. The absolute splitting below 3 MHz is considered as 0 for the sake of the limited resolution. Error bars of the fitted value denote 95% confidence interval.

scale scalability. Thus, a single Si_3N_4 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.

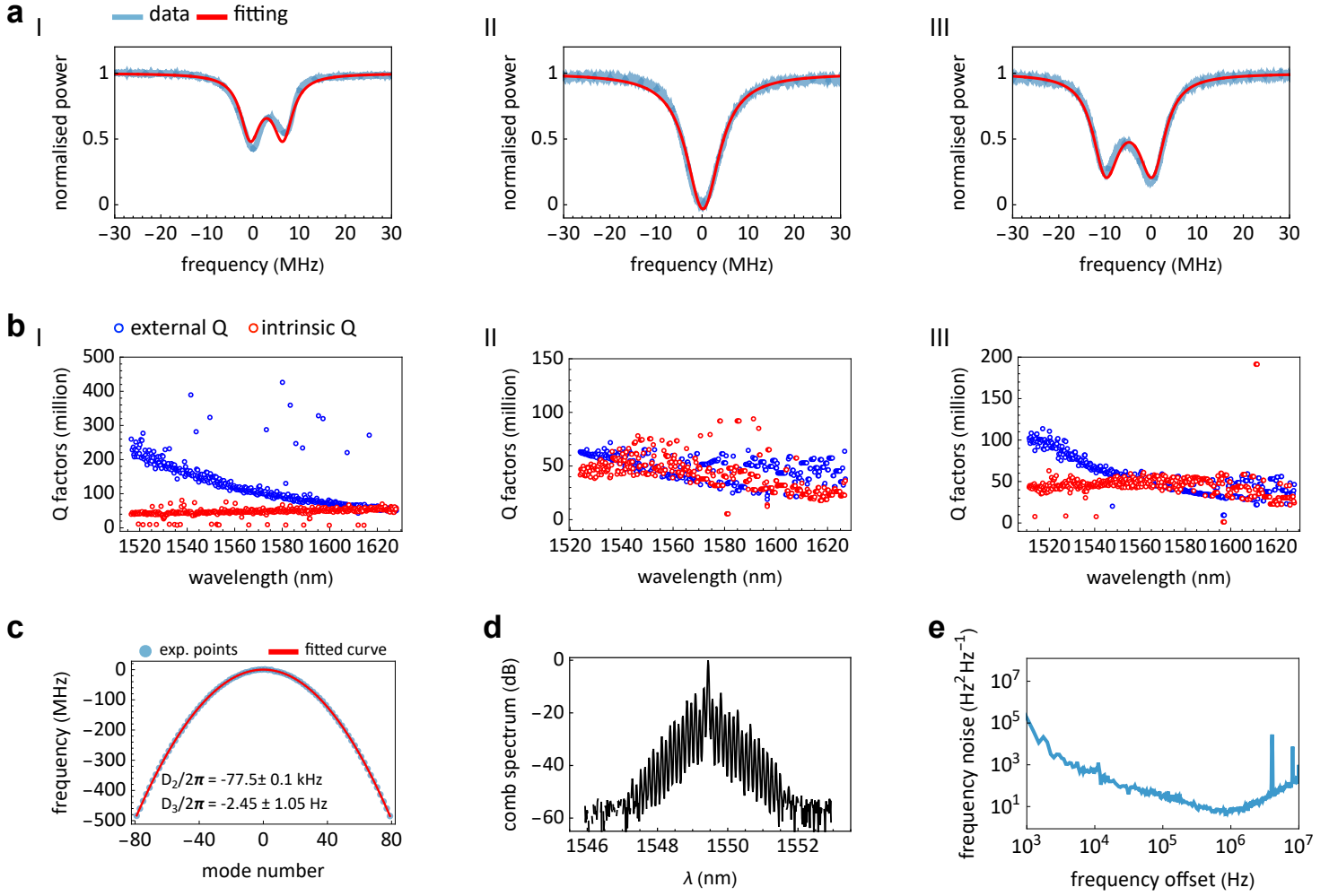


Figure S3 Wafer-scale characterisations of foundry-fabricated Si_3N_4 microresonator and microcombs from different dies on the same wafer. Each column represents data obtained from a microresonator on a different die (Chip I, II, III) with slightly varied designs. (a), Measured normalised transmission 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 external (blue) and intrinsic (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.

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 lithography, etching and deposition 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 undoped InGaAsP layers with a 1.25 μm bandgap wavelength, 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 electrically 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. The phase modulation was achieved using a single-arm electro-optic PM (EOPM), while IM was implemented using Mach-Zehnder interferometers (MZIs) with dual-arm PMs (with 1.25 mm length, 25 GHz bandwidth) for loss balance and high extinction ratio (ER).

2 Theory and modeling of the self-injection-locking dark-pulse microcomb

The dark-pulse microcomb is generated through the self-injection locking effect using a 100 nm-thick Si₃N₄ microresonator with normal group velocity dispersion. The equations utilised in our numerical simulation are listed as follows⁶⁸:

$$\frac{dN}{d\tau} = \frac{f_e^2}{\tilde{g}_0 \tilde{\kappa}_{\text{WGM}}^2} (\tilde{\kappa}_l - N|a_l|^2) + \tilde{\kappa}_N (\tilde{\kappa}_l / \tilde{g}_l - N), \quad (\text{S2})$$

$$\frac{da_l}{d\tau} = [-i\tilde{\zeta}_0 - iv_{\tilde{\zeta}}\tau + (1 + i\alpha_g)N\tilde{g}_l - \tilde{\kappa}_l] a_l - \frac{\tilde{\kappa}_{\text{Laser}}\tilde{\kappa}_{\text{WGM}}}{f_e} e^{i\varphi_B} b [-D_1(t - \varphi_B/\omega_0)], \quad (\text{S3})$$

$$\dot{a} = -a + id_2 \frac{\partial^2 a}{\partial \phi^2} + id_3 \frac{\partial^3 a}{\partial \phi^3} + iB_b + ia(|a|^2 + 2P_b) - f_e a_l e^{i\omega_0 t_s}, \quad (\text{S4})$$

$$\dot{b} = -b + id_2 \frac{\partial^2 b}{\partial \phi^2} + id_3 \frac{\partial^3 b}{\partial \phi^3} + iB_a + ib(|b|^2 + 2P_a). \quad (\text{S5})$$

In our model, Eq. (S2) and Eq. (S3) stem from the laser rate equations^{69,70}, while Eq. (S4) and Eq. (S5) are derived from the Lugiato-Lefever equations⁷¹⁻⁷³, corresponding to the forward and backward waves, respectively. The interaction between the laser and WGM is facilitated by the final terms of Eq. (S3) and Eq. (S4), which signify the feedback to the laser cavity mode and the pump to the forward WGM, each incorporating a time delay. Here, $\tau = \kappa_0 t/2$ is the time normalised by the average loaded cavity linewidth κ_0 , which is the sum of intrinsic cavity linewidth $\kappa_{0,\text{int}}$ and external cavity linewidth $\kappa_{0,\text{ext}}$; N, a_l represent the carrier concentration and the normalised photon field amplitude in the laser (we assume a single-mode laser field in the laser); $\tilde{g}_l, \tilde{g}_0$ denote the normalised carrier gain coefficient and the normalised nonlinear gain coefficient, respectively, satisfying

$$\tilde{g}_l = g_l / \kappa_0, \quad (\text{S6})$$

$$\tilde{g}_0 = \frac{n_2 c_0}{n_0^2} \frac{\hbar \omega_0^2}{\kappa_0}, \quad (\text{S7})$$

where g_l is the carrier gain coefficient, n_2 is the Kerr coefficient, c_0 is the velocity of light in vacuum, $\hbar$ is the reduced Planck constant, ω_0 is the angular frequency of centre WGM and we assume that all the WGMs have the same gain coefficient as mode ω_0 ; $\tilde{\kappa}_l, \tilde{\kappa}_N$ are the relaxation rate (or linewidth) of the inverse population and laser mode. The expected normalised pump f_e is defined as following⁶⁸:

$$f_e = \sqrt{\tilde{g}_0 \tilde{\kappa}_{\text{WGM}}} \sqrt{\frac{\tilde{g}_l J_N - \tilde{\kappa}_N \tilde{\kappa}_l}{\tilde{g}_l \tilde{\kappa}_l}}, \quad (\text{S8})$$

in which we defined the generalised coupling coefficients $\tilde{\kappa}_{\text{Laser}}$ and $\tilde{\kappa}_{\text{WGM}}$ as:

$$\tilde{\kappa}_{\text{Laser}} = \frac{T_0}{\tau_l} \sqrt{\frac{2\kappa_c \tau_W}{\kappa_0}} \sqrt{\frac{n_{\text{Coupler}} S_C}{n_L S_{\text{Laser}}}}, \quad (\text{S9})$$

$$\tilde{\kappa}_{\text{WGM}} = \frac{T_0}{R_0} \sqrt{\frac{2\kappa_c}{\kappa_0 \tau_W}} \sqrt{\frac{n_L S_{\text{Laser}}}{n_C S_{\text{Coupler}}}}, \quad (\text{S10})$$

with amplitude reflectivity and transmission of laser output mirror R_0, T_0 , coupling linewidth κ_c , round trip time of laser and WGM τ_l, τ_W , and the field to power coefficients $n_L S_{\text{Laser}}$ and $n_C S_{\text{Coupler}}$. We defined the normalised injection current as $J_N = \frac{2I}{eV_l \kappa_0}$ with current I , the effective laser mode volume V_l and elemental electron charge e .

In Eq.(S3), $\tilde{\zeta}_0 = 2(\Omega_l - \omega_0)/\kappa_0, v_{\tilde{\zeta}}$ are initial detuning (Ω_l is the initial laser mode frequency) and detuning speed of laser normalised by WGM linewidth, φ_B is the locking phase from laser to microresonator and α_G is the Henry factor. We define the normalised second and third order dispersion coefficient $d_2 = 2D_2/\kappa_0, d_3 = 3D_3/\kappa_0$ and note that the FSR equals $D_1/2\pi$, where we ignore higher-order dispersion terms.

In the left-hand sides of Eq.(S3) and Eq.(S4), the $a(\tau, \phi)$ and $b(\tau, \phi)$ are respectively normalised forward and backward photon spatial field amplitudes defined as

$$a = \sum a_\mu^+ e^{i\mu\phi}, \quad (\text{S11})$$

$$b = \sum a_\mu^- e^{i\mu\phi}, \quad (\text{S12})$$

in which $a_\mu^\pm$ is normalised forward (backward) μ order modal amplitudes. The coupling between forward and backward WGM is done by $B_{a,b}$, which can be expressed by normalised forward-backward coupling coefficient of μ th mode β_μ and $a_\mu^\pm$:

$$B_a = \sum \beta_\mu a_\mu^+ e^{i\mu\phi}, \quad (\text{S13})$$

$$B_b = \sum \beta_\mu^* a_\mu^- e^{i\mu\phi}. \quad (\text{S14})$$

Meanwhile, we could get β_μ from mode splitting⁷⁴:

$$\beta_\mu = \delta\omega_\mu / \kappa_0 \quad (\text{S15})$$

f_e	1.5	α_g	0.0	ω_0	$2\pi \times 193.4$ THz	φ_B	3
κ_0	$2\pi \times 16.627$ MHz	$\tilde{\kappa}_l$	1×10^5	$\tilde{\kappa}_N$	36.0862	$\tilde{\kappa}_{\text{Laser}}$	107.8925
$\tilde{\kappa}_{\text{WGM}}$	1.0526	$\tilde{g}_0$	$8.1617 \times 10^{-23} \text{ m}^3$	$\tilde{g}_l$	$1.9144 \times 10^{-20} \text{ m}^3$	FSR	30.033 GHz
d_2	-0.0373	d_3	1.3027×10^{-4}	ζ_0	20	μ_ξ	-0.02

Table S1 The parameters employed for simulating and designing the dark-pulse microcomb.

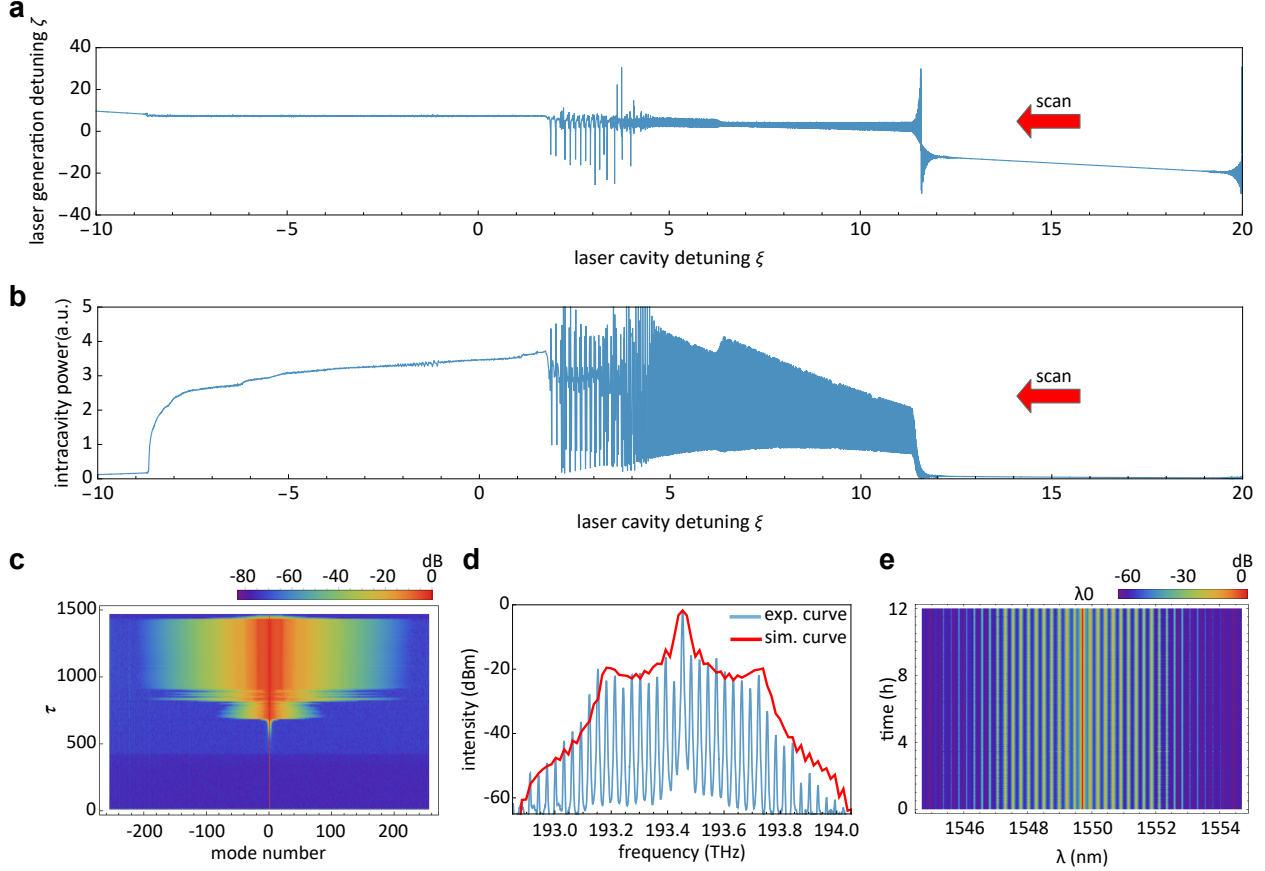


Figure S4 Simulation of the dark-pulse microcomb. (a), Tuning curve (laser generation detuning ζ vs. laser cavity detuning ξ). A long steady detuning curve indicates the generation of dark-pulse. (b), Resonance curve (intracavity power vs. laser cavity detuning ξ). (c), Evolution of the dark-pulse microcomb with initial continuous-wave pumping and random vacuum noise. The time unit is normalised to loaded cavity linewidth κ_0 . (d), Simulated and experimental output spectrum of the dark-pulse microcomb. (e), Spectral stability characterisation of microcomb. The microcomb's spectrum was collected every minute with an optical spectrum analyser over consecutive 12 hours. The data were used to calculate the output intensity fluctuations presented in Fig. 2e of the main text.

Measured mode splitting of the microresonator is shown in Fig. S2d (the example of mode 0) and Fig. S2e (summary of all modes). In Eq.(S3) and Eq.(S4), the terms $ia(|a|^2 + 2P_b)$ and $ib(|b|^2 + 2P_a)$ come from Kerr effect, where $P_a = \int |a|^2 d\phi / 2\pi$, $P_b = \int |b|^2 d\phi / 2\pi$ are average intensities over the microresonator, and the factor 2 is due to cross-phase modulation (XPM).

Following the above theory, we simulated the generation of the self-injection-locked dark-pulse microcomb with experimental parameters. The reduced parameters utilised for simulating are outlined in Tab. S1. As we concerned about the mode centred at ω_0 , the β values of the middle 128 modes are calculated from the measured mode splittings and the rest are assumed as the average value of $\beta_{\text{ave}} = 0.2991$. In addition, to speed up numerical calculations, taking into account the arbitrariness of the selection of length units, the actual value of $\{\tilde{g}_l, \tilde{g}_0\}$ brought into the simulation is $\{5, 0.0043\}$, while the ratio of $\tilde{g}_l, \tilde{g}_0$ remained unchanged.

The simulation results are shown in Fig. S4. With the detuning $\xi = \xi_0 + v_\xi \tau$ sweeping from 20 to -10 (from blue detuning to red detuning), the laser generation detuning $\zeta = -\frac{d}{d\tau} \arg a_l$ rises linearly at first, and locks to a steady state after fluctuations within the detuning range of -5 to 0, as is demonstrated in Fig. S4a, suggesting the presence of a dark-pulse state. The intracavity power can be estimated by summing up all the $|a_l|^2$ and $|b_l|^2$ values, which remains a consistent power level within the minus detuning range of -5 to 0, indicated in Fig. S4b. The simulated spectrum with detuning presented in Fig. S4c illustrates the evolution of the dark-pulse. The spectrum of the microcomb obtained in our experiment agreed well with the numerical simulation results, initialised with random noise, as depicted in Fig. S4d. The stability test shown in Fig. S4e and Fig. 2e in main text demonstrated the stable operation of the self-injection-locked microcomb.

3 The SNS-TF-QKD protocol and numerical simulation

While our network leverages a wavelength-division-multiplexing(WDM)-based architecture for multi-user communication, it basically functions as multiple pairs of two-user communications. We implemented the sending-or-not-sending twin-field QKD (SNS-TF-QKD) protocol between each pairwise users. In this section, we provide a concise overview of the protocol and assess the system's performance using experimental parameters.

3.1 The SNS-TF-QKD protocol

We implement the SNS-TF-QKD protocol using the four-intensity decoy state method⁴⁹. Additionally, we account for the finite-key size effect to establish more reasonable lower bounds on the secure key rate⁷⁵. When a pair of users (say Alice and Bob) opt to communicate, they proceed through the following steps:

- 1) **States preparation.** Alice and Bob prepare the bright reference signals for global phase tracking and the weak quantum signals for key distribution. For the quantum signals, they prepare the coherent state $|\sqrt{\mu_{A(B)}}e^{i\delta_{A(B)}+i\phi_{A(B)}}\rangle$, where $\mu_{A(B)}$ denotes the mean photon number chosen by Alice (Bob), $\delta_{A(B)}$ and $\phi_{A(B)}$ denote the phases added by Alice (Bob) and global phases, respectively. They will randomly choose the time window to be a signal window with the probability P_z or a decoy state window with the probability $1 - P_z$. At a signal window, they decide not to send the signal with the probability P_{z0} or to send the weak coherent state with $\mu = \mu_z$ with the probability $1 - P_{z0}$. At a decoy state window, they choose to send the weak coherent state with $\mu = \{0, \nu_1, \nu_2\}$ with the probabilities $\{P_0, P_1, 1 - P_0 - P_1\}$. Alice and Bob each independently select a random phase shift $\delta_{A(B)}$ for phase randomisation in every transmission.
- 2) **Measurement.** The third-party Charlie (i.e. the server node) announces the global phases $\phi_{A(B)}$ by measuring the bright reference signals and interfering the quantum signals at the beamsplitter. Charlie records and announces the effective response of the single-photon detectors when one and only one detector registers a click.
- 3) **Information publication and sifting.** Alice and Bob publicly announce their selection of the signal or decoy state windows, along with the intensities and phases during the decoy state windows. When both opt for the signal window, it is denoted as the Z-window: Z_{ij} , where $i(j) = \{1, 0\}$ corresponds to the specific case when Alice (Bob) decides to send the signal or not. All other situations are referred to as the X-window (even in cases of intensity mismatches): X_{ij} , where $i(j) = \{0, 1, 2\}$ corresponds to the specific case when Alice (Bob) decides to send the weak coherent state with intensities $\mu = 0, \nu_1, \nu_2$. In a special circumstance where they both select the decoy state with $\mu = \nu_1$, the phases must adhere to the following conditions:

$$1 - |\cos[(\delta_A - \delta_B) - (\phi_B - \phi_A)]| \leq |\epsilon_\phi| \quad (\text{S16})$$

where ϵ_ϕ is a predefined parameter close to 0. In this work, the global phases $\phi_{A(B)}$ are tracked in real time but not compensated. Thus, the valid time windows are determined by all the announced phase information (including $\delta_{A(B)}$ and $\phi_{A(B)}$) to ensure that the value of $|\cos[(\delta_A - \delta_B) - (\phi_B - \phi_A)]|$ is approximately to 0 or π : $|\cos[(\delta_A - \delta_B) - (\phi_B - \phi_A)]| \leq \frac{\Delta}{2}$ or $|\cos[(\delta_A - \delta_B) - (\phi_B - \phi_A) - \pi]| \leq \frac{\Delta}{2}$, where Δ represents the threshold.

- 4) **Parameter estimation.** The outcomes generated by the single-photon signals can be extracted from the results described earlier. The count rate Q_z and error rate E_z in Z-window could be directly calculated from the experimental results, while the single-photon count rate $Q_{1,z}$ and phase-flip error rate $e_{1,z}^{ph}$ can be estimated using the decoy-state method.
- 5) **Error correction and private amplification.** During the data post-processing, a certain number of bits are consumed, and the final secure keys are distilled.

3.2 Numerical simulation

To provide clarity for the forthcoming equations, let's define the symbols used in the context: N_{tot} : the total number of bits sent. N_{ij} : the number of bits when choosing different intensities. $N_{\Delta+(-)}$: the number of bits sent satisfy Eq.(S16). n_{ij} : the recorded effective events. $n_{11\text{error}}$: effective but error bits in X_{11} -window. n_{signal} : effective and correct bits in Z-window. n_{error} : effective but error bits in Z-window.

Taking the finite-key size effect into consideration, the secure key rate (in bits/pulse) can be calculated as:

$$R = P_z^2 \left\{ 2P_{z0}(1 - P_{z0})\mu_z e^{-\mu_z} Q_{1,z} \left[1 - H(e_{1,z}^{ph}) \right] - f_{EC} Q_z H(E_z) \right\} - \frac{1}{N_{\text{tot}}} \left(\log_2 \frac{2}{\epsilon_{cor}} + 2 \log_2 \frac{1}{\sqrt{2}\epsilon_{PA}\hat{\epsilon}} \right) \quad (\text{S17})$$

where f_{EC} is the error correction coefficient (set to be 1.1) and the parameters in post-processing are chosen to be $\epsilon_{cor} = \epsilon_{PA} = \hat{\epsilon} = 1.0 \times 10^{-10}$. The function $H(x) = -x \log_2 x - (1-x) \log_2 (1-x)$ is the binary Shannon entropy. To obtain the lower bound of Eq.(S17), we have to estimate the lower bound of $Q_{1,z}$ and the upper bound of $e_{1,z}^{ph}$, which can be inferred from the results Q_1 and e_1^{ph} in the X-window.

The lower bound of Q_1 :

$$\begin{aligned} \langle Q_1 \rangle &\geq \langle \underline{Q}_1 \rangle \\ &= \frac{\nu_2^2 e^{\nu_1} (\langle \underline{Q}_{01} \rangle + \langle \underline{Q}_{10} \rangle) - \nu_1^2 e^{\nu_2} (\langle \underline{Q}_{02} \rangle + \langle \underline{Q}_{20} \rangle) - 2(\nu_2^2 - \nu_1^2) \langle \underline{Q}_{00} \rangle}{2\nu_1\nu_2(\nu_2 - \nu_1)} \end{aligned} \quad (\text{S18})$$

where $Q_{jk} = \frac{n_{jk}}{N_{jk}}, \{jk\} = \{00, 01, 10, 02, 20, 11\}$ denotes the effective count rate when choosing different intensities. The overlines and underlines denote the estimated upper and lower bounds obtained using the Chernoff bound after considering statistical fluctuations:

$$\langle \underline{Q}_{jk} \rangle = \frac{Q_{jk}}{1 + \delta_{jk}}, \langle \overline{Q}_{jk} \rangle = \frac{Q_{jk}}{1 - \delta_{jk}} \quad (\text{S19})$$

where $\delta_{ij} = \delta(n_{ij}, \epsilon), \delta(x, y) = \frac{1}{2x} \left(-\ln \frac{y}{2} + \sqrt{(\ln \frac{y}{2})^2 - 8(\ln \frac{y}{2})x} \right), \epsilon = 1.0 \times 10^{-10}$.

The upper bound of e_1^{ph} :

$$\langle e_1^{ph} \rangle \leq \langle \overline{e_1^{ph}} \rangle = \frac{\langle n_{11error} / (N_{\Delta+} + N_{\Delta-}) \rangle - \frac{1}{2} e^{-2\nu_1} \langle Q_{00} \rangle}{2\nu_1 e^{-2\nu_1} \langle \underline{Q}_1 \rangle} \quad (\text{S20})$$

After obtaining the expected value of Q_1 and e_1^{ph} , we use the Chernoff bound again to determine the true bounds, considering statistical fluctuations.

$$\begin{aligned} \underline{Q}_{1,z} &= \langle \underline{Q}_1 \rangle (1 - \delta_1^c) \\ \overline{e_{1,z}^{ph}} &= \langle \overline{e_1^{ph}} \rangle (1 + \delta_1'^c) \end{aligned} \quad (\text{S21})$$

where:

$$\begin{aligned} \delta_1^c &= \delta \left(2P_z^2 P_{z0} (1 - P_{z0}) \mu_z e^{-\mu_z} N_{\text{tot}} \langle \underline{Q}_1 \rangle, \epsilon \right) \\ \delta_1'^c &= \delta \left(2P_z^2 P_{z0} (1 - P_{z0}) \mu_z e^{-\mu_z} N_{\text{tot}} \underline{Q}_{1,z} \langle \overline{e_1^{ph}} \rangle, \epsilon \right) \end{aligned} \quad (\text{S22})$$

The lower bound of the secure key rate can be calculated by substituting Eq.(S21) into Eq.(S17). The parameters in Tab.S2 are used for numerical simulation and experimental settings. Given the relationship between channel transmittance η_c and distance L that $\eta_c = 10^{-\alpha_c L/20}$, where α_c denotes the channel loss coefficient, the secure key rate under different communication distances can be estimated, which is plotted in Extended Data Figure 1, with the finite-key size of $N_{\text{tot}} = 10^{12}$, dark count rate $p_d = 2.4 \times 10^{-9}$, detection efficiency $\eta_d = 0.75$ and misalignment error $e_d = 0.02$. As a future achievable improvement, we give the curve with a dark count rate $p_d = 1 \times 10^{-10}$ and detection efficiency $\eta_d = 0.90$ in the asymptotic case, showing that the communication distance can be further extended.

N_{tot}	P_z	P_{z0}	P_0	P_1	μ_z	ν_1	ν_2	p_d	e_d	η_d	Δ
10^{12}	0.72	0.976	0.25	0.5	0.52	0.21	0.41	2.4×10^{-9}	0.02	0.75	$\pi/16$

Table S2 The parameters for implementing the SNS-TF-QKD protocol and simulating key rates.

4 Experimental implementation of the SNS-TF-QKD in the network

4.1 Experimental setup

The QKD network involves the collaborative high-speed control of multiple integrated photonic chips. The core task is to realise the global phase locking and tracking of the distant optical fields under the WDM network architecture to generate a large number of remote twin fields, and then implement the quantum state generation, manipulation and detection based on the weak coherent state light sources to implement the long-distance, multi-user QKD network. The network system could be divided into four parts: dark-pulse microcomb generation at the server node, quantum keys encoding at the client nodes, optical field transmission through fibre channels across the WDM network, and single-photon detection at the server node. Figure 3 and Figure 4 in the main text report 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. A detailed experimental setup for paired TF-QKD client chips is shown in Fig. S5.

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 EDFA 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.

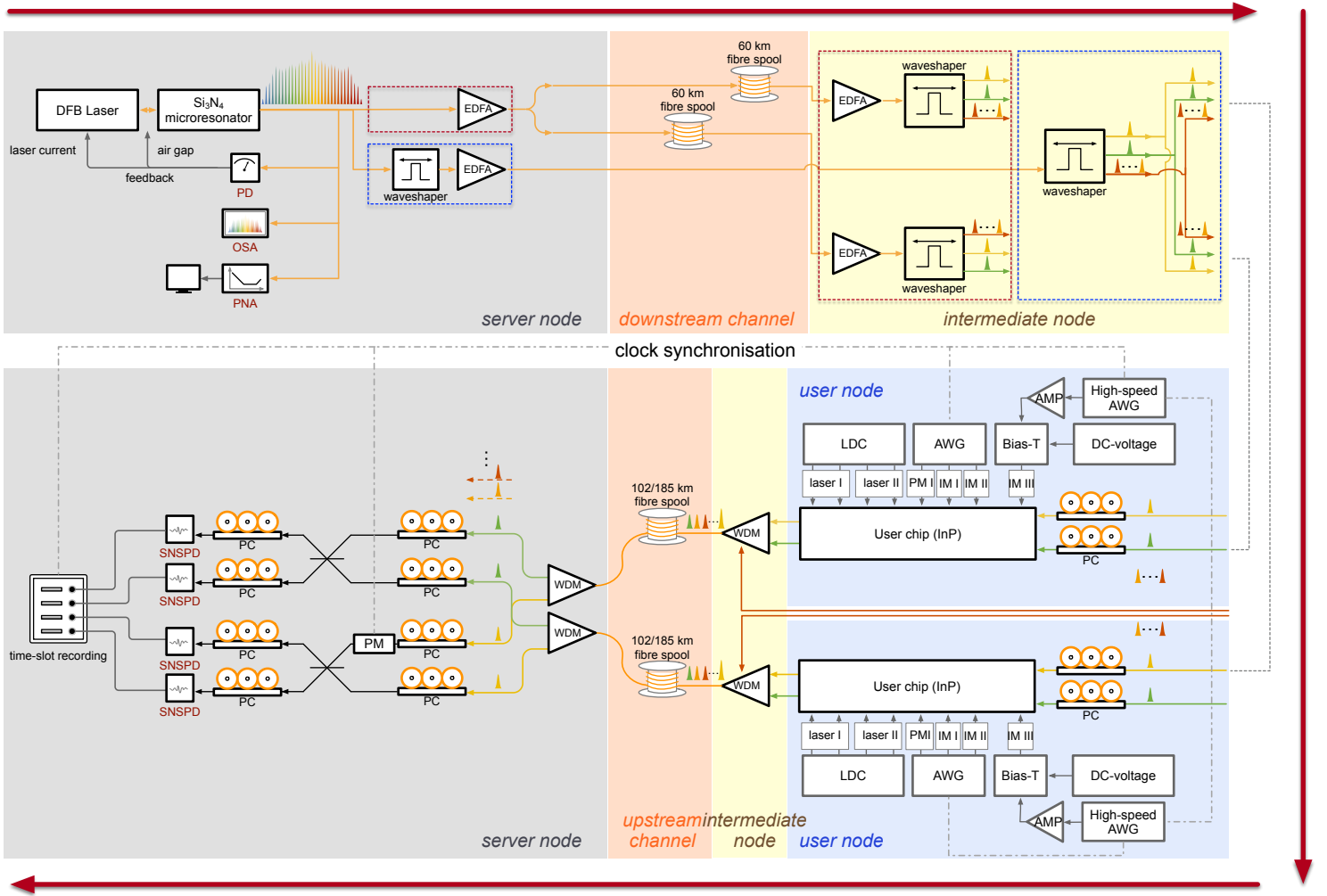


Figure S5 A full diagram of the experimental setup for TF-QKD between paired QKD client-chips in the network. The TF-QKD network between 20 client chips centralised with a microcomb laser, which provides all chip-level resources required for parallel and simultaneous 20-client QKDs in the network. We 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.

Integrated microcombs matching standard ITU channel spacing (e.g., 50/100 GHz) can be readily implemented⁷⁶, 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.

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

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. Figure 2i 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: As shown in Fig.S5, the process can be regarded as a loop consisting of the following sequence: server node $\rightarrow$ long downstream backbone channel $\rightarrow$ intermediate node $\rightarrow$ user node $\rightarrow$ intermediate node $\rightarrow$ long upstream backbone channel $\rightarrow$ 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.

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 networks²¹, 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 microcombs exhibit exceptional coherence and can simultaneously serve as optical synchronisers and RF synthesizers⁶⁰. This approach would enable fully optical synchronisation while maintaining the TF QKD system's functionality.

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.S6, 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).

Temporal workflow of the quantum networking system: The basic experimental workflow is shown in Fig.3a. Initially, the microcomb drove DBR lasers, locking their wavelengths and phases. Continuous-wave signals from the locked DBR lasers were carved into pulses with a 200 MHz repetition rate by IM III. The modulation signals from IM I, II, and PM I were segmented into synchronised cycles of 20 ms. The dual- λ phase tracking was implemented within 5 ms windows to measure the quantum-reference phase difference Φ_d , enabling continuous operation through 15 ms key distributions. During the first 5 ms phase estimation period, IM I and II were optimised to maximise the count rates at the server node, while PM I was modulated to execute a 4-phase estimation method (a single phase sampling point was defined using a series of 100 μ s 4-phase modulated bins). During the period of 15 ms for quantum communication, IM I and II accurately modulated the intensity based on the decoy state requirements, while PM I facilitated phase randomisation and key encoding simultaneously. A single-cycle sawtooth voltage in the 15 ms period (spanning 2π phase scan) applied to PM I achieved an effective 3×10^6 -level phase randomisation, sufficient for decoy-state and TF-QKD implementations (see section 4.2). At the server node, the PM for the reference light was synchronised to provide real-time global phase tracking, and single-photon interference between paired QKD chips and detections returns the secure raw keys. Device clocks were currently synchronised via electrical signals (see Fig.S5), while in future microcomb could enable practical clock synchronisations.

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.

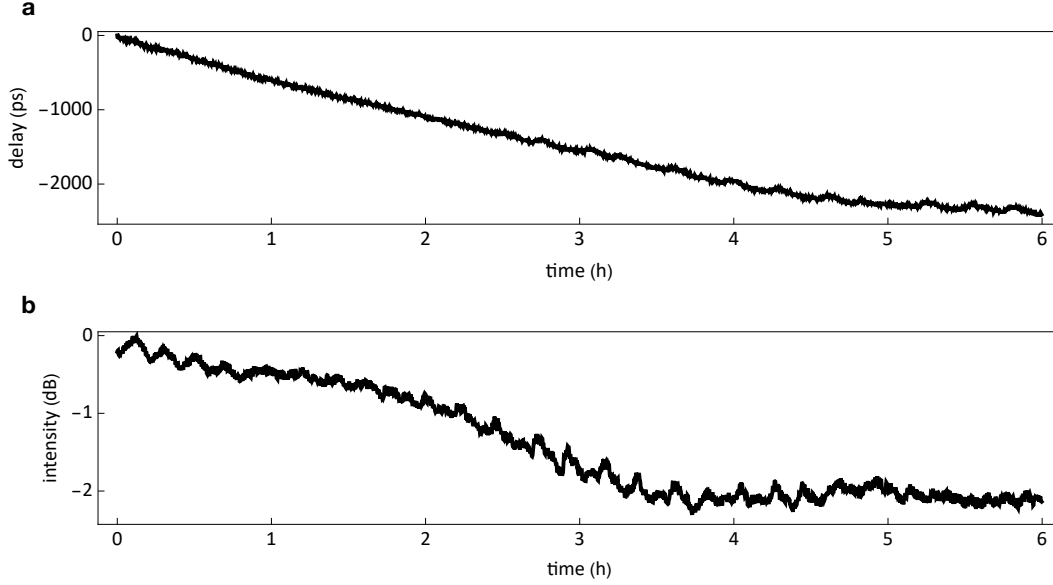


Figure S6 Characterisation of temporal delay drift and polarisation drift. (a) and (b), Delay and polarisation drift tests in the 185 km fibre channel. Data points were acquired at 10-second intervals for both parameters, with each condition measured independently to ensure accurate characterisation.

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 settings⁷⁷. 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 information⁷⁷. 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 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.[78], 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 current experiment, the level of phase randomisation was characterised by interference outcome recording with the server node's SNSPDs for simplicity. Additionally, 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.

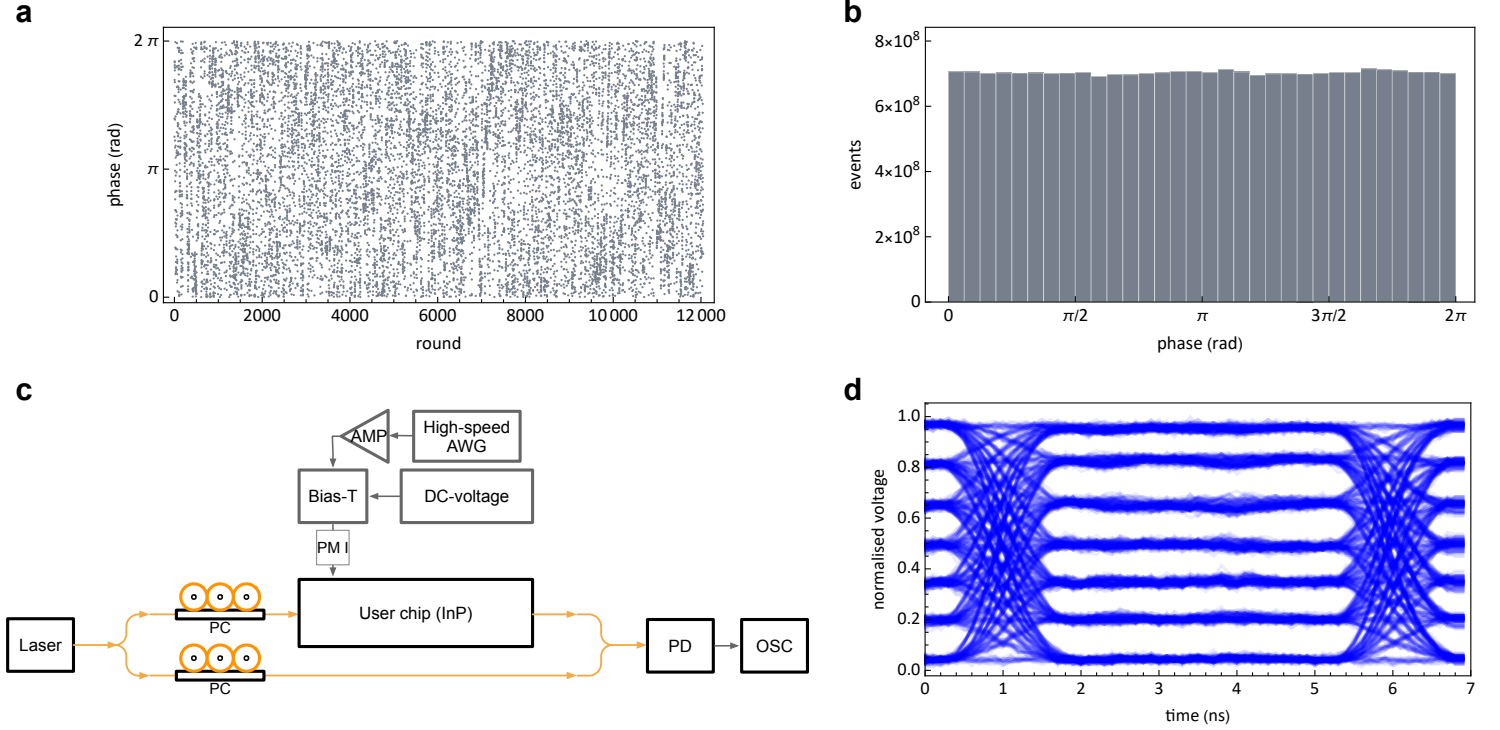


Figure S7 Device and system characterisations for the phase randomisation verification. (a), Experimental results of $[(\delta_{A,r} - \delta_{B,r}) - (\phi_{B,q} - \phi_{A,q})]$ for paired QKD users $\{A_1, B_1\}$ during quantum communication at the distance of 370 km. The first 12,000 round was displayed, 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 ν_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.

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^{17,79}.

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^{17,18,20} and postselection^{19,47,48} 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.

For future quantum networks with extended distances, the phase fluctuation (ϕ_r and ϕ_q) 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 length¹⁴. 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_q 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 lab¹⁸, and 7.80 rad/ms with 856-km-long (428 km + 428 km) symmetric fibre channel in the field test⁸⁰. 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 postselection¹⁹. 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.

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 chips²⁸, 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.

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^{17,79}, 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 section⁸¹ 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 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.

	λ_{-5}	λ_{-4}	λ_{-3}	λ_{-2}	λ_{+3}	λ_{+4}	λ_{+5}	λ_{+6}	λ_{+7}	λ_{+8}
counts of D_{qL} (ref. off)	19.14±3.98	19.39±5.65	18.57±5.15	16.90±2.51	13.03±3.64	15.19±4.78	11.54±2.20	13.61±3.35	11.61±3.69	16.60±2.98
counts of D_{qR} (ref. off)	20.92±3.76	18.26±4.21	15.76±4.25	17.48±6.30	15.44±3.33	21.96±3.06	12.96±3.83	14.36±4.75	13.35±3.46	15.15±4.15
counts of D_{qL} (ref. on)	19.90±2.67	20.51±3.21	16.05±4.44	17.13±6.97	11.65±3.20	14.82±5.50	10.90±3.84	13.98±3.61	12.20±3.21	16.77±5.43
counts of D_{qR} (ref. on)	20.95±3.57	17.82±3.67	15.89±6.03	24.44±6.97	14.74±3.29	25.20±4.31	11.00±1.91	15.00±3.89	12.12±4.09	15.77±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.

4.5 Phase estimation with four-phase method in the network

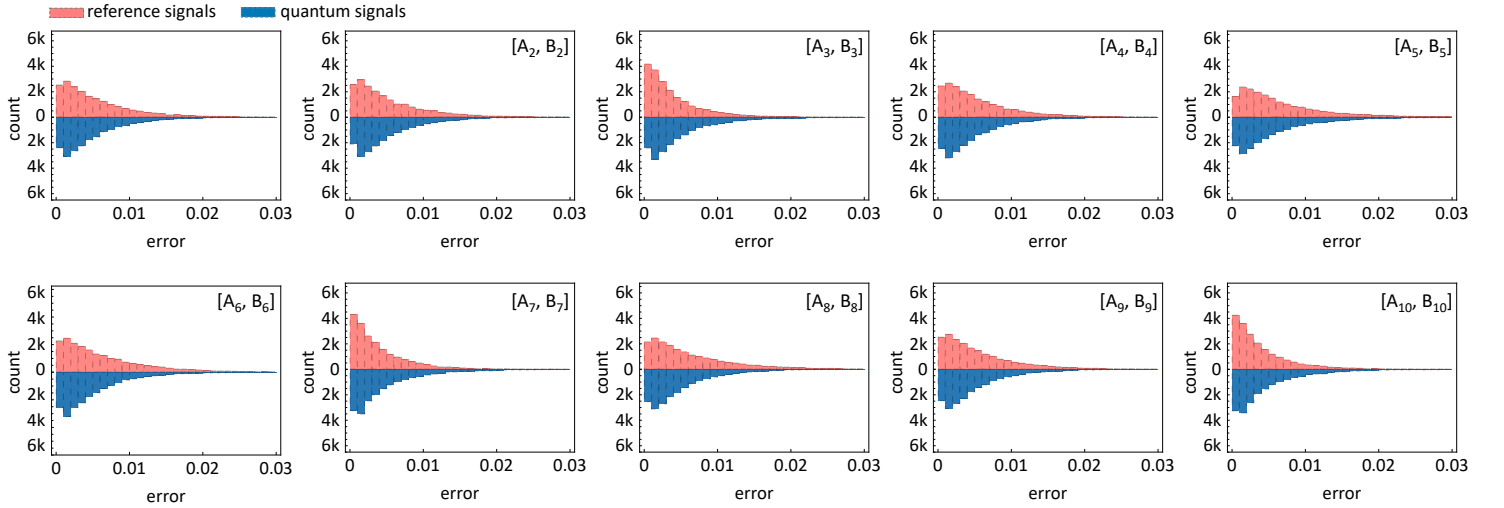


Figure S8 The errors of the four-phase estimation method. The histograms correspond to the statistical distribution of the estimation errors in the network. Each graph has a total of 20,000 points.

In this work, we estimated the phase fluctuations induced by fibre channels according to the interference results of quantum and reference signals at the server node respectively. The precision of phase tracking is directly affected by the accuracy of phase estimation at each moment. To mitigate the impact of Raman noise photons, the phase estimation light received at the server node was weak that SNSPDs were used for detection, which means that we need to recover the phase with limited detector counts. For an interferometer, the ratio of clicks from one of the output ports is:

$$P_1 = \frac{n_1}{n_1 + n_2} = \frac{1 + \cos\Delta\phi}{2} \quad (\text{S26})$$

where n_1, n_2 represent the clicks of two output ports within a fixed integration time and $\Delta\phi$ is the phase difference of two paths. This means the phases inferred from the interference will result in multiple values. To circumvent this problem and make full use of the limited count to accurately estimate the phases, we executed the four-phase method in the network. As mentioned in the main text, every phase estimation point consisted of four segments, each of which actively attached additional phase $\{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\}$ in one path. Assuming that the phase difference $\Delta\phi$ remains constant during this time period, we could get a vector of theoretical ratios:

$$\mathbf{P} = [P, P_{\frac{\pi}{2}}, P_{\pi}, P_{\frac{3\pi}{2}}] = \left[\frac{1 + \cos\Delta\phi}{2}, \frac{1 + \cos(\Delta\phi + \frac{\pi}{2})}{2}, \frac{1 + \cos(\Delta\phi + \pi)}{2}, \frac{1 + \cos(\Delta\phi + \frac{3\pi}{2})}{2} \right] \quad (\text{S27})$$

By minimising the distance between the theoretical vector and the vector of experimental ratios $\mathbf{Q} = [Q, Q_{\frac{\pi}{2}}, Q_{\pi}, Q_{\frac{3\pi}{2}}]$, we could estimate $\Delta\phi$ with high accuracy. To verify this method, we defined the estimation error to be:

$$e = \left| \frac{\min\|\mathbf{X}\|_2}{\max\|\mathbf{X}\|_2} \right|^2 \quad (\text{S28})$$

where $\mathbf{X} = \mathbf{Q} - \mathbf{P}$ and $\|\cdot\|_2$ represents the L2 norm. The low errors in Fig. S8, which correspond to the phase points shown in Fig. 3b and c in the main text, verified the exact estimation at each moment.

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 important⁴⁴, 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. [75]. 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 method⁵¹), 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.

5 Towards real-field implementation of integrated-photonic TF-QKD networks

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 amplified spontaneous emission (ASE) noise 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. S9a. The generated microcomb first underwent spectral equalisation via a programmable filter (wave shaper I) to normalise power across all wavelength channels (Figs. S9b-d), ensuring uniform gain and signal-to-noise ratio (SNR) for each comb line (λ_{-5} to λ_{+8}). The attenuation pattern uploaded to the wave shaper I was calculated in Fig. S9c. 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. S9e). After post-transmission amplification (EDFA II), we analysed individual comb lines via wave shaper II filtering. The power spectral densities (Fig. S9f) confirm preserved low-noise characteristics across all channels. Comparative linewidth measurements before/after transmission (Fig. S9g) 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^{19,48,79}. 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 kilometres¹⁹. 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^{18,82}. 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.

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. S10a. 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) technology⁸³, which combines high electro-optic efficiency (> 90% shifting efficiency⁵⁷) with broad operational bandwidth (± 641 GHz⁸⁴). Nonlinear approaches leveraging $\chi^{(2)}$ or $\chi^{(3)}$ processes in periodically poled lithium niobate waveguides have demonstrated 55% single-photon conversion efficiency⁸⁵ with broadband operation across the entire C-band⁸⁶, while four-wave mixing Bragg scattering in microresonator-based silicon photonic devices offers alternative implementations^{87,88}. 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. S10c, where beatnote measurements between original and frequency-shifted comb lines demonstrate equally narrow linewidths. Advanced microcomb feedback control can further enhance comb line phase stabilisation⁸⁹, implemented locally at the server node without requiring additional client-side hardware. Alternatively, heterogeneous integration techniques⁹⁰ offer complementary approaches for improving phase stability.

Another critical consideration involves addressing asymmetric channel lengths between users, a key challenge in real-field applications. In QKD implementations, channel length asymmetries cause differential loss for quantum states transmitted by different users, requiring protocol parameter optimisation to accommodate these variations⁹¹. A more immediate challenge arises in experimental implementations: asymmetric channel lengths eventually form a giant asymmetric MZI, thereby dominating laser phase noise in the interference output. While adding compensating fibres to balance arm lengths can improve symmetry²¹, this approach becomes increasingly impractical in large-scale

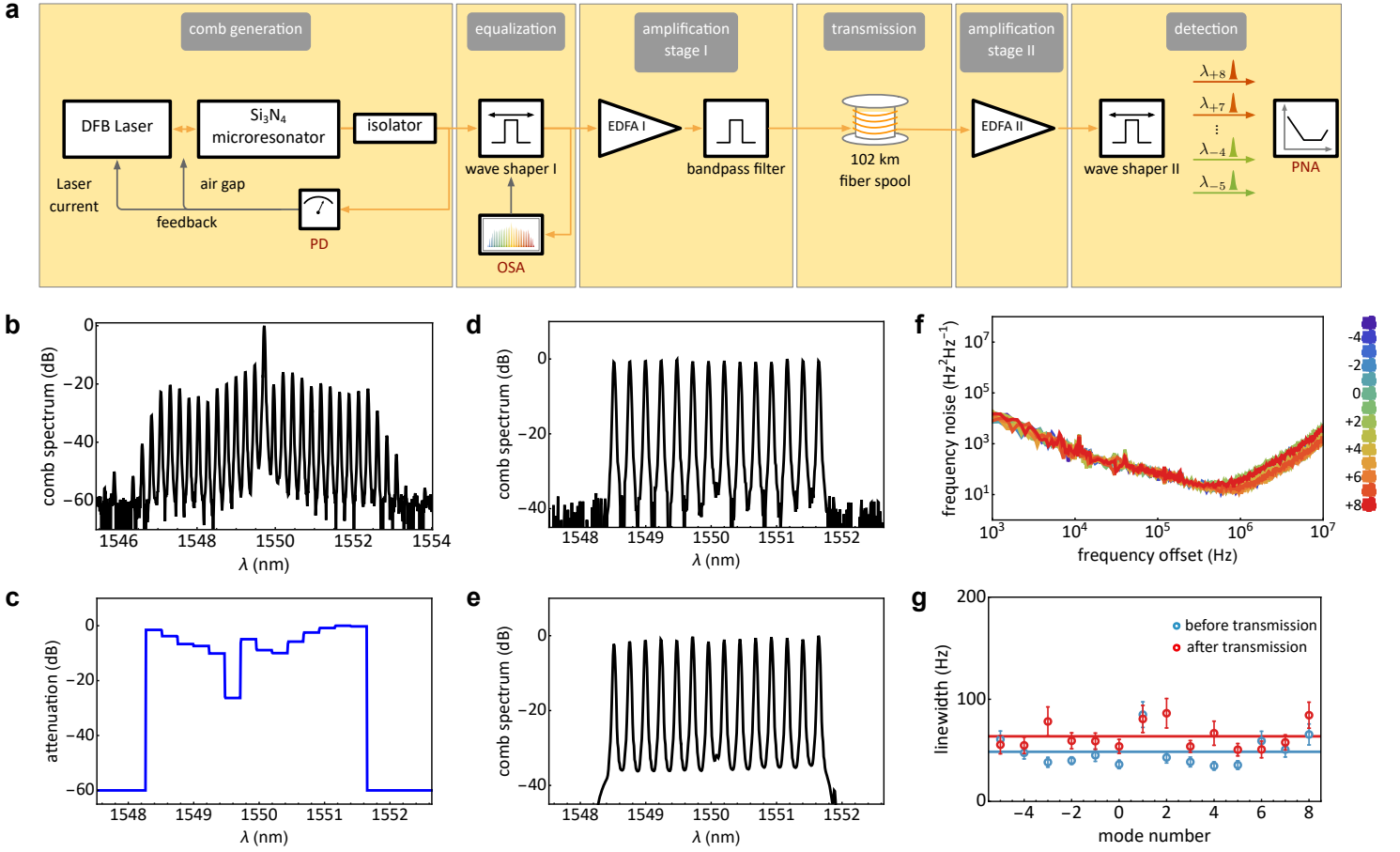


Figure S9 Characterisation of comb lines after transmission in long-haul downstream fibres. (a), Schematic diagram for experimental setup. Comb lines generated from the self-injection locking system were spectrally equalised and pre-amplified (EDFA I) before entering a 102 km-long fibre channel. The second amplification stage (EDFA II) was introduced to compensate for attenuation after transmission through the long fibre. The frequency noise of each comb line was analysed. (b), Measured spectrum of the original microcomb. (c), Calculated wave-shaper pattern for spectrum equalisation. (d), Equalised spectrum by applying wave shaper I. λ_{-5} to λ_{+8} were selected as the target channels. (e), Measured spectrum before transmission. All spectra are normalised to the maximum power. (f), Characterisation of frequency noises after transmission and EDFA II. (g), Comparison between the measured intrinsic linewidths before/after transmission. Error bars denote ± 1 standard deviation.

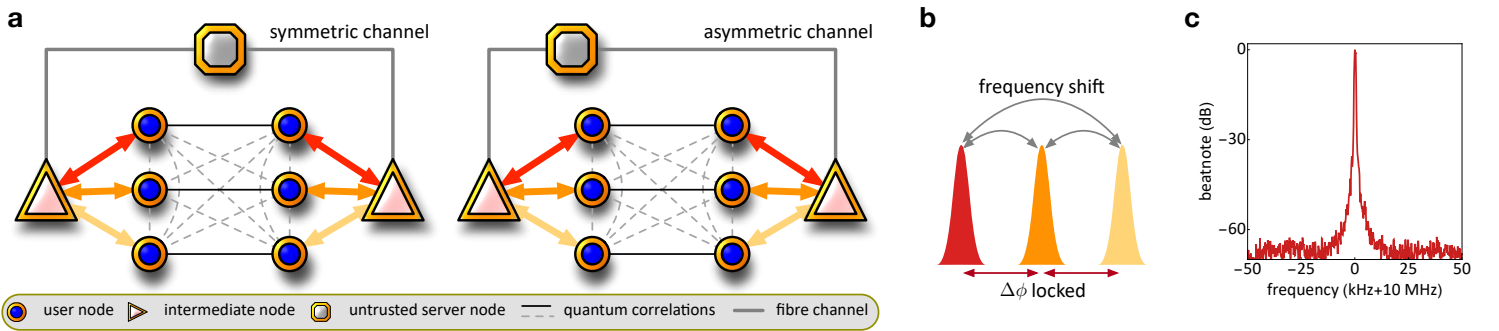


Figure S10 Extension to fully connected and asymmetric networks. (a), Schematic diagram of fully connected networks under symmetric configuration (nearly identical user-to-server channel lengths) or asymmetric configuration (substantial user-to-server length variations). Solid black lines denote pairwise quantum correlations between same-wavelength users, while dashed grey 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.

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 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 feasible⁹², which shows the potential to enhance tolerance to channel length disparities in TF-QKD.

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.

6 Security analysis and discussion

Although QKD is well known to be unconditionally secure in its theoretical formulation, practical implementations face security vulnerabilities that emerge from discrepancies between ideal protocols and physical devices. These loopholes, which may stem from either inherent device imperfections or active attackers, enable potential eavesdropping without detection by legitimate parties. Such vulnerabilities do not invalidate QKD's mathematical security proofs, but rather highlight the critical importance of device characterisation and countermeasure implementation in real-world systems. As TF-QKD's measurement-device-independent (MDI) nature inherently eliminates detector-side vulnerabilities, the security assessment now focuses on the transmitter components. Notably, we establish the global phase references by optical injection locking (OIL) at the client nodes. Whilst this method demonstrated excellent feasibility in previous TF-QKD implementations^{21,29,44}, extra vulnerability could be brought to the client as it needs to acquire seeding light from the central node outside the users. Despite the widespread adoption of OIL in QKD, rigorous security analyses of this technique remain absent from existing literature. We present a brief security assessment of our transmitter design, beginning with an examination of regular vulnerabilities, followed by specific considerations unique to injection-locked architectures.

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), and 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 vulnerabilities⁹³. In our experiment, the random encoded phase was set by applying a sawtooth voltage on the phase modulator on the client chip, which provides an equivalent discrete randomisation level of 3 million effectively emulating the random phase settings⁷⁷ (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^{94,95}. These problems are usually specific to the system implementation, and need 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^{96,97}. 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 port⁹⁸. 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.

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 attack⁹⁹, which could be classified as a Trojan horse attack. Using an independent laser for the transmitter and performing injection locking^{21,28,29,44}, 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^{15,100}, 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 levels¹⁰¹. 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 distribution¹⁰².

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.

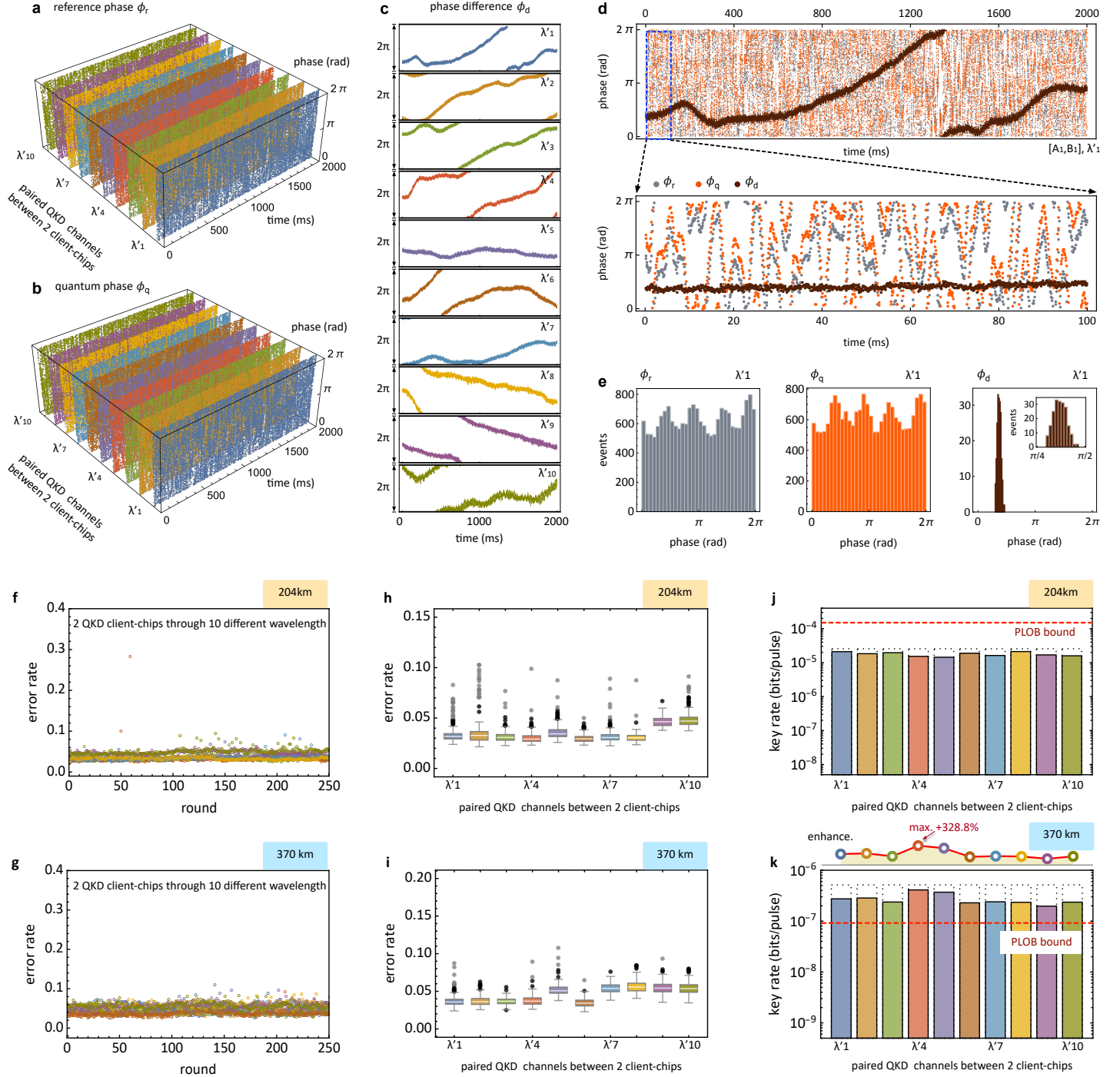


Figure S11 Phase tracking and TF-QKD with two QKD client-chips $\{A_1, B_1\}$ through ten different paired wavelength channels λ'_i where $i = [1, 2, \dots, 10]$. In Fig.3 and Fig.4, we report the TK-QKD network with 20 InP QKD transmitter chips at 10 different wavelength channels λ'_i . Here, we implemented an additional experiment: two QKD client-chips, where on-chip DBR lasers were wavelength-tuned and injection-locked to distinct wavelengths λ'_i for the TF-QKD network, $i = [1, 2, \dots, 10]$. This demonstration aims to show the flexibility of our client chip in WDM networks, where the generic hardware configuration can accommodate multi-wavelength operational requirements. Full data is provided in Tab. S6. **(a)-(c)**, Experimental characterisation of phases across the TF-QKD network. (a), phases for the reference signals (Φ_r) at the wavelength of λ_0 , (b), phases for the quantum signals (Φ_q) at the wavelength of λ'_i , and (c), their relative phase differences $\Phi_d = \Phi_r - \Phi_q$. The fibre network employed 370 km upstream (185+185 km) and predominantly short downstream links. Data were collected sequentially for each pairwise wavelength channel. **(d)**, an example of phase distributions for the λ'_1 channel, with a zoomed-in view focusing on the first 100 ms. **(e)**, histogram distributions of Φ_r and Φ_q over 2 seconds and Φ_d over 100 ms. Error rates and key rates are measured for the 2 QKD client-chips $\{A_1, B_1\}$ through 10 quantum channels at different wavelengths λ'_i . **(f)** and **(h)**, Segmented QBER in the X-basis and their statistical distributions in the 204 km upstream fibre channels. **(g)** and **(i)**, 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 75×10^6 bins. In **(h)** and **(i)**, the box plot shows the mean, quartiles, and extremes. **(j)** and **(k)**, Measured secure key rates in 204 km and 370 km fibre channels, respectively. The dotted boxes represent the theoretical value at that distance, while the red dashed line represents the PLOB-repeaterless bound at that distance. In all subplots, coloured points and chart bars represent different paired QKD wavelength channels.

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204 km

		[A ₁ , B ₁]		[A ₂ , B ₂]		[A ₃ , B ₃]		[A ₄ , B ₄]		[A ₅ , B ₅]	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N ₀₀	108,315,000,000	1,663	1.535E-08	1,827	1.687E-08	2,091	1.930E-08	1,774	1.638E-08	1,238	1.143E-08
Z ₀₀	468,677,160,000	6,835	1.458E-08	3,075	6.561E-09	9,892	2.111E-08	6,760	1.442E-08	7,326	1.563E-08
X ₀₁	113,940,000,000	114,929,630	1.009E-03	117,902,649	1.035E-03	116,715,232	1.024E-03	115,539,229	1.014E-03	120,400,772	1.057E-03
X ₁₀	113,940,000,000	117,094,489	1.028E-03	113,843,131	9.991E-04	114,155,652	1.002E-03	114,617,129	1.006E-03	120,008,022	1.053E-03
X ₀₂	56,970,000,000	101,921,471	1.789E-03	97,643,834	1.714E-03	99,931,996	1.754E-03	100,895,091	1.771E-03	99,931,996	1.754E-03
X ₂₀	56,970,000,000	100,034,135	1.756E-03	99,194,233	1.741E-03	102,770,732	1.804E-03	99,883,466	1.753E-03	98,863,703	1.735E-03
Z _{0z}	10,542,840,000	24,401,626	2.315E-03	24,472,875	2.321E-03	23,539,977	2.233E-03	23,315,867	2.212E-03	23,822,601	2.260E-03
Z _{z0}	10,542,840,000	24,147,675	2.290E-03	23,657,325	2.244E-03	24,134,744	2.289E-03	23,336,350	2.213E-03	23,790,672	2.257E-03
Z _{zz}	237,160,000	1,070,588	4.514E-03	1,057,483	4.459E-03	1,067,596	4.502E-03	1,079,037	4.550E-03	1,063,322	4.484E-03
X _{11correct}	22,500,000,000	2,933,861	1.304E-04	2,968,194	1.319E-04	3,247,286	1.443E-04	3,092,101	1.374E-04	2,989,488	1.329E-04
X _{11error}		105,781	4.701E-06	111,847	4.971E-06	107,254	4.767E-06	113,839	5.060E-06	102,462	4.554E-06
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		3.480E-02	2.171E-02	3.631E-02	2.156E-02	3.197E-02	2.210E-02	3.551E-02	2.274E-02	3.314E-02	2.199E-02

		[A ₆ , B ₆]		[A ₇ , B ₇]		[A ₈ , B ₈]		[A ₉ , B ₉]		[A ₁₀ , B ₁₀]	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N ₀₀	108,315,000,000	611	5.641E-09	2,679	2.473E-08	2,409	2.224E-08	2,544	2.349E-08	2,324	2.146E-08
Z ₀₀	468,677,160,000	2,377	5.072E-09	11,049	2.357E-08	9,870	2.106E-08	11,246	2.400E-08	8,852	1.889E-08
X ₀₁	113,940,000,000	124,023,437	1.088E-03	113,856,966	9.993E-04	121,452,693	1.066E-03	111,655,910	9.800E-04	114,720,468	1.007E-03
X ₁₀	113,940,000,000	117,720,621	1.033E-03	114,031,945	1.001E-03	113,063,456	9.923E-04	114,154,024	1.002E-03	117,867,653	1.034E-03
X ₀₂	56,970,000,000	93,244,502	1.637E-03	96,111,339	1.687E-03	103,659,872	1.820E-03	102,200,625	1.794E-03	99,560,062	1.748E-03
X ₂₀	56,970,000,000	100,759,603	1.769E-03	98,149,647	1.723E-03	98,286,782	1.725E-03	98,524,835	1.729E-03	98,711,616	1.733E-03
Z _{0z}	10,542,840,000	22,906,909	2.173E-03	23,688,707	2.247E-03	23,290,499	2.209E-03	23,929,568	2.270E-03	24,321,955	2.307E-03
Z _{z0}	10,542,840,000	24,441,029	2.318E-03	24,117,574	2.288E-03	24,354,525	2.310E-03	23,611,650	2.240E-03	23,641,038	2.242E-03
Z _{zz}	237,160,000	1,075,460	4.535E-03	1,085,440	4.577E-03	1,074,256	4.530E-03	1,081,638	4.561E-03	1,064,945	4.490E-03
X _{11correct}	22,500,000,000	3,068,892	1.364E-04	3,021,969	1.343E-04	3,112,051	1.383E-04	2,877,859	1.279E-04	3,026,129	1.345E-04
X _{11error}		90,772	4.034E-06	90,671	4.030E-06	97,501	4.333E-06	88,927	3.952E-06	91,463	4.065E-06
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		2.873E-02	2.226E-02	2.913E-02	2.242E-02	3.038E-02	2.225E-02	2.997E-02	2.247E-02	2.934E-02	2.190E-02

370 km

		[A ₁ , B ₁]		[A ₂ , B ₂]		[A ₃ , B ₃]		[A ₄ , B ₄]		[A ₅ , B ₅]	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N ₀₀	108,315,000,000	1,851	1.709E-08	1,726	1.594E-08	2,381	2.198E-08	1,720	1.588E-08	558	5.152E-09
Z ₀₀	468,677,160,000	8,131	1.735E-08	7,398	1.578E-08	9,749	2.080E-08	6,316	1.348E-08	2,874	6.132E-09
X ₀₁	113,940,000,000	2,662,213	2.337E-05	2,427,457	2.130E-05	2,495,285	2.190E-05	2,464,063	2.163E-05	2,448,405	2.149E-05
X ₁₀	113,940,000,000	2,479,013	2.176E-05	2,502,589	2.196E-05	2,509,934	2.203E-05	2,552,702	2.240E-05	2,511,751	2.204E-05
X ₀₂	56,970,000,000	2,009,709	3.528E-05	2,167,709	3.805E-05	2,185,208	3.836E-05	2,162,461	3.796E-05	2,164,695	3.800E-05
X ₂₀	56,970,000,000	2,096,070	3.679E-05	2,145,614	3.766E-05	2,142,888	3.761E-05	2,133,076	3.744E-05	2,218,982	3.895E-05
Z _{0z}	10,542,840,000	530,302	5.030E-05	531,811	5.044E-05	531,058	5.037E-05	514,739	4.882E-05	526,629	4.995E-05
Z _{z0}	10,542,840,000	516,341	4.898E-05	516,394	4.898E-05	519,084	4.924E-05	507,201	4.811E-05	538,872	5.111E-05
Z _{zz}	237,160,000	25,051	1.056E-04	23,135	9.755E-05	24,008	1.012E-04	23,596	9.949E-05	24,763	1.044E-04
X _{11correct}	22,500,000,000	54,629	2.428E-06	59,013	2.623E-06	61,198	2.720E-06	52,689	2.342E-06	48,811	2.169E-06
X _{11error}		2,245	9.978E-08	2,219	9.862E-08	2,527	1.123E-07	2,192	9.742E-08	2,000	8.889E-08
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		3.947E-02	3.073E-02	3.624E-02	2.830E-02	3.965E-02	3.114E-02	3.994E-02	2.844E-02	3.936E-02	2.528E-02

		[A ₆ , B ₆]		[A ₇ , B ₇]		[A ₈ , B ₈]		[A ₉ , B ₉]		[A ₁₀ , B ₁₀]	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N ₀₀	108,315,000,000	1,202	1.110E-08	1,992	1.839E-08	2,613	2.412E-08	2,574	2.376E-08	2,592	2.393E-08
Z ₀₀	468,677,160,000	5,218	1.113E-08	9,751	2.081E-08	11,027	2.353E-08	9,586	2.045E-08	8,428	1.798E-08
X ₀₁	113,940,000,000	2,516,446	2.209E-05	2,520,515	2.212E-05	2,521,560	2.213E-05	2,489,288	2.185E-05	2,475,752	2.173E-05
X ₁₀	113,940,000,000	2,502,611	2.196E-05	2,434,246	2.136E-05	2,640,001	2.317E-05	2,565,909	2.252E-05	2,439,943	2.141E-05
X ₀₂	56,970,000,000	2,156,315	3.785E-05	2,146,550	3.768E-05	2,219,401	3.896E-05	2,220,905	3.898E-05	2,164,455	3.799E-05
X ₂₀	56,970,000,000	2,147,769	3.770E-05	2,148,992	3.772E-05	2,205,349	3.871E-05	2,081,238	3.653E-05	2,145,329	3.766E-05
Z _{0z}	10,542,840,000	530,004	5.027E-05	521,871	4.950E-05	511,709	4.854E-05	497,109	4.715E-05	521,645	4.948E-05
Z _{z0}	10,542,840,000	525,862	4.988E-05	530,004	5.027E-05	517,601	4.910E-05	504,727	4.787E-05	517,879	4.912E-05
Z _{zz}	237,160,000	24,654	1.040E-04	24,156	1.019E-04	24,666	1.040E-04	24,978	1.053E-04	24,485	1.032E-04
X _{11correct}	22,500,000,000	40,526	1.801E-06	44,007	1.956E-06	50,952	2.265E-06	46,738	2.077E-06	63,220	2.810E-06
X _{11error}		1,762	7.831E-08	1,769	7.862E-08	1,921	8.538E-08	1,960	8.711E-08	2,293	1.019E-07
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		4.167E-02	2.751E-02	3.864E-02	3.123E-02	3.633E-02	3.351E-02	4.025E-02	3.335E-02	3.500E-02	3.069E-02

Table S5 Full experimental data sets for 20 paired TF-QKD client-chips $\{A_i, B_i\}$ through ten different wavelength channels λ_i^j in the network. Data in this table is used to plot Fig.3 and Fig.4.

204 km

		λ'_1		λ'_2		λ'_3		λ'_4		λ'_5	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N_{00}	105,850,000,000	6,808	6.433E-08	2,818	2.663E-08	4,560	4.308E-08	6,674	6.305E-08	3,206	3.030E-08
Z_{00}	453,850,000,000	22,666	4.994E-08	17,900	3.944E-08	17,529	3.862E-08	28,964	6.382E-08	12,345	2.720E-08
X_{01}	110,200,000,000	128,386,358	1.165E-03	117,617,992	1.067E-03	117,676,297	1.068E-03	127,619,681	1.158E-03	116,633,748	1.058E-03
X_{10}	110,200,000,000	118,121,557	1.072E-03	121,573,848	1.103E-03	120,160,455	1.090E-03	120,842,928	1.097E-03	123,528,459	1.121E-03
X_{02}	55,100,000,000	98,620,258	1.790E-03	96,263,112	1.747E-03	96,780,969	1.756E-03	100,239,787	1.819E-03	104,506,575	1.897E-03
X_{20}	55,100,000,000	102,417,733	1.859E-03	99,694,417	1.809E-03	100,371,827	1.822E-03	105,115,834	1.908E-03	107,894,983	1.958E-03
Z_{0z}	10,875,000,000	27,077,091	2.490E-03	27,208,096	2.502E-03	27,559,148	2.534E-03	26,851,920	2.469E-03	29,020,372	2.669E-03
Z_{z0}	10,875,000,000	28,295,908	2.602E-03	26,751,500	2.460E-03	26,632,996	2.449E-03	27,548,775	2.533E-03	26,317,366	2.420E-03
Z_{zz}	260,420,000	1,392,962	5.349E-03	1,384,112	5.315E-03	1,372,629	5.271E-03	1,362,860	5.233E-03	1,368,432	5.255E-03
$X_{11\text{correct}}$		3,251,160	2.229E-04	3,299,112	2.262E-04	3,086,412	2.116E-04	3,695,172	2.534E-04	3,440,448	2.359E-04
$X_{11\text{error}}$	14,583,300,000	113,882	7.809E-06	121,378	8.323E-06	100,226	6.873E-06	171,262	1.174E-05	127,821	8.765E-06
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		3.384E-02	2.493E-02	3.549E-02	2.532E-02	3.145E-02	2.501E-02	4.429E-02	2.495E-02	3.582E-02	2.434E-02

		λ'_6		λ'_7		λ'_8		λ'_9		λ'_{10}	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N_{00}	105,850,000,000	7,740	7.313E-08	4,034	3.811E-08	7,289	6.886E-08	5,847	5.524E-08	3,965	3.746E-08
Z_{00}	453,850,000,000	30,715	6.768E-08	36,671	8.080E-08	39,276	8.654E-08	28,577	6.297E-08	24,732	5.450E-08
X_{01}	110,200,000,000	117,821,123	1.069E-03	122,978,804	1.116E-03	121,464,170	1.102E-03	126,969,376	1.152E-03	125,654,160	1.140E-03
X_{10}	110,200,000,000	121,834,319	1.106E-03	115,325,611	1.047E-03	126,236,983	1.146E-03	129,198,010	1.172E-03	124,529,087	1.130E-03
X_{02}	55,100,000,000	99,571,311	1.807E-03	104,010,334	1.888E-03	101,605,874	1.844E-03	102,400,852	1.858E-03	105,817,198	1.920E-03
X_{20}	55,100,000,000	101,886,382	1.849E-03	104,905,299	1.904E-03	101,344,322	1.839E-03	105,105,569	1.908E-03	94,048,487	1.707E-03
Z_{0z}	10,875,000,000	27,404,482	2.520E-03	27,270,744	2.508E-03	27,110,064	2.493E-03	26,906,956	2.474E-03	28,150,210	2.589E-03
Z_{z0}	10,875,000,000	26,575,348	2.444E-03	27,057,796	2.488E-03	27,051,323	2.487E-03	26,982,231	2.481E-03	25,967,994	2.388E-03
Z_{zz}	260,420,000	1,402,165	5.384E-03	1,379,257	5.296E-03	1,350,628	5.186E-03	1,345,074	5.165E-03	1,321,933	5.076E-03
$X_{11\text{correct}}$		3,271,284	2.243E-04	3,278,604	2.248E-04	3,357,150	2.302E-04	3,706,770	2.542E-04	3,759,072	2.578E-04
$X_{11\text{error}}$	14,583,300,000	100,678	6.904E-06	107,233	7.353E-06	107,245	7.354E-06	180,650	1.239E-05	190,931	1.309E-05
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		2.986E-02	2.586E-02	3.167E-02	2.540E-02	3.096E-02	2.502E-02	4.647E-02	2.486E-02	4.834E-02	2.428E-02

370 km

		λ'_1		λ'_2		λ'_3		λ'_4		λ'_5	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N_{00}	105,850,000,000	6,220	5.877E-08	3,459	3.268E-08	6,166	5.826E-08	5,745	5.428E-08	3,523	3.329E-08
Z_{00}	453,850,000,000	20,740	4.570E-08	13,927	3.069E-08	26,170	5.766E-08	25,976	5.724E-08	16,551	3.647E-08
X_{01}	110,200,000,000	3,015,031	2.736E-05	3,082,909	2.798E-05	2,946,892	2.674E-05	3,111,765	2.824E-05	3,026,235	2.746E-05
X_{10}	110,200,000,000	3,106,445	2.819E-05	2,946,991	2.674E-05	3,122,405	2.833E-05	3,150,707	2.859E-05	3,209,568	2.912E-05
X_{02}	55,100,000,000	2,701,840	4.904E-05	2,585,595	4.693E-05	2,591,384	4.703E-05	2,747,325	4.986E-05	2,626,055	4.766E-05
X_{20}	55,100,000,000	2,541,091	4.612E-05	2,688,576	4.879E-05	2,676,372	4.857E-05	2,691,588	4.885E-05	2,708,080	4.915E-05
Z_{0z}	10,875,000,000	693,301	6.375E-05	702,087	6.456E-05	684,162	6.291E-05	677,287	6.228E-05	685,480	6.303E-05
Z_{z0}	10,875,000,000	700,593	6.442E-05	697,173	6.411E-05	691,655	6.360E-05	635,695	5.845E-05	696,410	6.404E-05
Z_{zz}	260,420,000	33,338	1.280E-04	31,843	1.223E-04	32,014	1.229E-04	30,878	1.186E-04	33,243	1.277E-04
$X_{11\text{correct}}$		80,503	5.520E-06	74,624	5.117E-06	72,066	4.942E-06	84,806	5.815E-06	70,045	4.803E-06
$X_{11\text{error}}$	14,583,300,000	3,074	2.108E-07	2,837	1.945E-07	2,758	1.891E-07	1,468	1.007E-07	2,313	1.586E-07
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		3.678E-02	3.735E-02	3.662E-02	3.167E-02	3.686E-02	4.057E-02	1.702E-02	4.150E-02	3.197E-02	3.478E-02

		λ'_6		λ'_7		λ'_8		λ'_9		λ'_{10}	
	exp. bits send	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate	exp. response	exp. count rate
N_{00}	105,850,000,000	2,544	2.404E-08	5,112	4.830E-08	8,454	7.988E-08	6,987	6.601E-08	4,094	3.868E-08
Z_{00}	453,850,000,000	29,167	6.427E-08	23,108	5.092E-08	36,393	8.019E-08	30,221	6.659E-08	23,088	5.087E-08
X_{01}	110,200,000,000	3,141,358	2.851E-05	3,257,268	2.956E-05	3,003,135	2.725E-05	2,769,561	2.513E-05	3,076,142	2.791E-05
X_{10}	110,200,000,000	2,945,230	2.673E-05	2,903,845	2.635E-05	3,235,574	2.936E-05	3,021,615	2.742E-05	3,290,307	2.986E-05
X_{02}	55,100,000,000	2,499,448	4.536E-05	2,634,195	4.781E-05	2,497,300	4.532E-05	2,396,377	4.349E-05	2,864,834	5.199E-05
X_{20}	55,100,000,000	2,655,838	4.820E-05	2,692,387	4.886E-05	2,677,150	4.859E-05	2,425,162	4.401E-05	2,739,256	4.971E-05
Z_{0z}	10,875,000,000	685,380	6.302E-05	674,066	6.198E-05	679,336	6.247E-05	713,190	6.558E-05	712,777	6.554E-05
Z_{z0}	10,875,000,000	684,837	6.297E-05	672,498	6.184E-05	658,104	6.052E-05	606,241	5.575E-05	718,848	6.610E-05
Z_{zz}	260,420,000	32,705	1.256E-04	32,714	1.256E-04	31,654	1.216E-04	32,974	1.266E-04	34,256	1.315E-04
$X_{11\text{correct}}$		83,576	5.731E-06	77,753	5.332E-06	74,953	5.140E-06	75,065	5.147E-06	77,035	5.282E-06
$X_{11\text{error}}$	14,583,300,000	2,991	2.051E-07	3,114	2.135E-07	3,132	2.148E-07	2,991	2.051E-07	3,102	2.127E-07
error rate		X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis	X basis	Z basis
		3.455E-02	4.320E-02	3.851E-02	3.981E-02	4.011E-02	4.842E-02	3.832E-02	4.571E-02	3.871E-02	3.851E-02

Table S6 Full experimental data sets for 2 TF-QKD client-chips $\{A_1, B_1\}$ through ten different wavelength channels λ'_i in the network. Data in this table is used to plot Fig.S11.