

Integrated polarization-entangled photon source for wavelength-multiplexed quantum networks

Corresponding Author: Professor Di Zhu

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

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This study on TFLN-based integrated polarization-entangled photon source represents an interesting advancement in the fields of the TFLN integrated photonics. I think that the motivation of the work is meaningful and the long-distance multi-user quantum network experiment is interesting, though the experiment relies on the looped back scheme. The proposed devices rely on the co-linear two cascaded PPLNs with different phase matching types (i.e. type 0 and 1). While the authors strongly argue the advantages of the design in the manuscript, I think that such scheme inherently has many drawbacks. In addition, I believe that several experimental results may require additional explanations. As a result, I cannot recommend the publication of the current manuscript in Nature Communication.

It is challenging for me to agree with the advantages of the proposed device. As noted in the manuscript, the authors argue that the proposed scheme has many advantages over the other designs including the scheme based on the PSRs and two non-collinear PPLNs. The authors point out that the existence of polarization-handling components in the previous works may have several limits and the. From my viewpoint, I believe that this might not be the case and I have listed the reasons in the followings.

1. Challenges in the brightness balance between TE- and TM- polarized biphotons: The authors control the length of the PPLNs for the balancing. I believe that the authors determine the ratio of the length of two PPLNs by the inverse ratio of the nonlinear tensor coefficients ($L_{\text{type0}}/L_{\text{type1}} \approx d_{31}/d_{33}$) and the authors somehow achieved (or argued) the maximally entangled states with the concurrence close to 1.

1a. However, it is very surprising to me because the measured brightness should be highly dependent on the polarization dependent losses for coupling and propagation. Also, Figure 2 clearly shows the polarization dependence. However, the authors achieved comparable brightness in Fig. 1d and Fig. 3. In addition to the Figure 2d, the authors should include the SHG intensity figures without normalization.

1b. Furthermore, the authors assume the negligible loss of 775 nm mode. I think that it might not be very realistic because the PPLNs are often accompanied with the periodic grooves. Even without poling process, the waveguide might have a nonnegligible loss at 775 nm.

1c. More importantly, the proposed cascading scheme might be very challenging to employ the additional electrical control circuits of the pump intensity for the brightness compensation.

1d. The authors should elaborate how they achieved comparable brightness for TETE and TMTM photon-pairs as shown in Fig. 1d.

2. Bandwidth problems of two different phase matching conditions: The proposed scheme inherently has different frequency bandwidths for the TETE and TMTM biphoton states. Such problems can be found in Fig. 2d. Specifically, the bandwidth of the type 1 phase matching is smaller than that of type 0. Although SPDC often has broad bandwidths, it does not guarantee comparable brightness for broadband widths. Interestingly, the authors report the flat brightness for many DWDM channels in Fig. 3f and 3g. I think that the authors should elaborate how they achieve such responses.

3. Robustness characteristics of the PSRs: Many polarization components can support the robust broadband operations because one can readily design the components using the concept of adiabaticity. Practically, I think that optimization of two poling recipes is more challenging than the optimization of the high-performance polarization components.

4. Fidelity argument is not strictly fair: The authors argue 97~99 % fidelities without performing the full quantum state tomography. I think that the authors should perform the quantum state tomography if the authors want to argue the best performance in the paper. At least, the authors should rather show the fringes for R/L basis instead of the H/V basis. This is because the phase information between the HH and VV state is important and the QST experiment can confirm that the state is not the mixed state but the entangled state.

In summary, the quality of the multi-user quantum network experiment is fine. It is hard for me to agree with the strengths of the proposed device. Also, some results and arguments need supporting data or careful explanations. In addition, the wavelength multiplexing has been very widely employed in the quantum network, so it might not be very novel. Unless the authors provide strong advantages of the proposed device design, it might not be suitable for the publication in Nature communication.

Reviewer #2

(Remarks to the Author)

The manuscript presents an on-chip polarization-entangled photon-pair source based on Thin-Film Lithium Niobate (TFLN). The core of the paper lies in the implementation of dual quasi-phase matching, which allows for sequential Type-0 and Type-I spontaneous parametric down-conversion within a single nanophotonic waveguide. This architecture generates high-fidelity Bell states without the need for external tools. The authors successfully demonstrate the utility of this source through wavelength-multiplexed entanglement distribution in a four-user quantum network across up to 50 km of metropolitan fiber.

The paper is well-written and addresses a topic of broad interest to both technologists and scientists. The work is very timely, fitting well within the current trajectory of quantum communications. Technically, the study is sound; the Materials and Methods section is comprehensive and provides sufficient detail to reasonably allow for the reproducibility of the results. Additionally, the inclusion of a table comparing the results with the current state-of-the-art is highly appreciated and provides clear context for the device's performance. While this is not the first demonstration of integrated polarization entanglement, given that similar results were achieved in silicon years ago and a few works on TFLN have recently appeared on preprint servers (actually, Ref. 34 has been already published: <https://journals.aps.org/prl/abstract/10.1103/sfj2-dcx1>), the high performance of this specific implementation make it a valuable contribution to the field.

I recommend the paper for publication following minor modifications. In particular, I am curious to see data regarding the long-term stability of the main parameters, such as the pair generation rate and the fidelity of the generated Bell state. Furthermore, it would be highly beneficial if the authors could identify and discuss the physical origins of any observed instabilities. Providing these stability metrics would further support the claim of the source's readiness for practical deployment.

Reviewer #3

(Remarks to the Author)

The authors have demonstrated a telecom polarization-entangled photon-pair source on thin-film lithium niobate (TFLN) employing dual quasi-phase matching in a single nanowaveguide, eliminating the need for interferometers, etc. while directly producing high-fidelity Bell states. Using this, they realized WDM-based entanglement distribution in a four-user quantum network deployed over metropolitan fiber links up to 50 km, without active time synchronization.

Here are some critical points/comments and suggestions:

1. In the network demonstration, a loopback configuration is used, effectively doubling the optical path length between the nodes. Does this imply that no active time synchronization of the time-stamper clocks was required between the user pairs? For a practical implementation consisting of users at distant location, time synchronization of their clocks is imperative. This is somehow not clear in the manuscript, and therefore the authors are suggested to clarify this and also highlight this in the abstract, to avoid any misconception.

2. In the four-user configuration (Alice, Bob, Charlie, and David), are all users interconnected with each other simultaneously (i.e., a fully connected network)? Or are only two users connected at a time, with entanglement distributed to a selected pair?

3. There's a huge literature pertaining to the efficient generation of polarization-entangled photon pairs, in ppLN crystals and waveguides. The review done in this paper is still insufficient. For example, quantum sources for the generation of efficient, fully guided-wave, compact and multiuser polarization-entangled photon pairs have a substantial background literature. (i) In this connection the current manuscript, its characterizations, results and inferences, etc. are very similar to the work done in the following references and, therefore, requires to be properly cited: Telecom source of tunable polarization-entanglement distribution up to 100 km for multi-user QKD over metro-area fiber-optic networks. APL Quantum, 2, 016102 (2025).

(ii) Additionally, since the polarization-entanglement generation approach is based on multiple periodic poling, it may be appropriate to include earlier theoretical work in this context. One example where this detail analysis of keeping different poling lengths for the Type-0 and Type-1 regions, while equating the respective SHG efficiencies can be found from the following reference:

Generation of two different polarization-entangled biphoton states in a potassium titanyl phosphate waveguide device with multiple periodic poling, Phys. Rev. A 101, 023832 (2020).

Including this work could help contextualize and compare your technique with similar multiple-poling approaches reported in integrated nonlinear platforms.

More Technical points:

4. In general, the quality of the figures require improvement as their resolution, contrast and clarity are quite poor.

In Fig. 1a, the optical micrograph of the fabricated D-QPM ppLN is not clear. Also, Fig. 1c,(ii) is not clear at all.

The resolution of Figs. 2 and 3 also seems poor. The authors are suggested to use a better software for plotting their figures or at least replace them with the original figures of better resolution.

Figures do not appear very clear. In Figs. 2 a, d, e, usage of Darker fonts is suggested. Also, in Figs. b and c the resolution needs to be improved. A calculated spectra corresponding to wavelength detuning could also be inserted as an inset in each figure.

5. How are the three microheaters tuned/controlled for controlling their phase-matching wavelengths and relative phases?

How does one ensure that these introduce only local heating, while the neighboring portion remains unaffected? This is crucial and some measurement pertaining to the same is mandatory. Why is any possibility for the transport of heat to slightly neighboring regions ruled out? Is there any earlier study related to the same effect?

6. The ppLN regions are sub-centimeter lengths. It was unclear What is the reason for measuring such high SHG and SPDC efficiencies? An SHG efficiency of ~56% from a 1-cm long TFLN region, given the nonlinear efficiencies of the two TFLN regions were the usual QPM d_{eff} depending on the d_{33} and d_{31} coefficients of LN, seems overestimated? Is it any different from a (similarly fiber-pigtailed) ppLN waveguide of the same poling period but usually of longer length that corresponds to similar SHG efficiencies? A comparison is suggested.

Did the authors also perform a temperature scan of the SHG power, showing the sinc² behavior? Generally, the conversion efficiency changes with the input FH pump power. Was this noticed in the measurements? How was this incorporated while calculating the normalized SHG efficiencies?

7. The entangled coincidence rate is quite low as evident from Fig. 1d although the raw coincidences and CAR are pretty good. What are the various losses and/or transmission efficiencies considered and how are they incorporated in the calculation of their source brightness, in particular to the Type-0 and Type-1 TFLN regions? Are they over-estimating the losses?

8. The phase-matching conditions and corresponding temperatures (PMT) are not mentioned clearly although the poling periods of the two regions are mentioned. The SHG experiments are performed at room temperature but their PMTs corresponding to the phase-matching condition are unclear. The authors are suggested to clearly provide the phase-matching temperature and corresponding pump wavelength required for degenerate SPDC in both Type-0 and Type-I configurations in the TFLN platform.

9. What's the emission bandwidth of the photon pairs in the respective Type-0 and Type-1 regions? Did the authors try to extract any information about the marginal spectra? Did the authors try to measure the resultant emission bandwidth of the photon pairs resulting from the device? The authors should quantify how much they actually imply when they mention "Far non-degenerate" and "near-degenerate".

10. What was the pump power kept for these measurements? Not much details are mentioned about the type and make of the pump laser/source in the various experiments (except at one place, about the Santec TSL-570), wavelength, linewidth of the pump that drives the SPDC processes in the D-QPM TFLN regions. Are SNSPD detectors used for all the experiments? In order to rule out any distinguishability between the photos from the different QPM processes, what was the pump wavelength that was ultimately maintained and how was that deciphered?

11. In page 4, what is this ultimate PMT kept for the two ppLN regions? What are the exact roles of the TEC module and the integrated microheaters in achieving the highest visibilities in the TPA that correspond to high entanglement fidelity along with a substantial rate of coincidences?

12. Specify any characterization graph measured to calibrate the DWDM used. How about the DWDM channel cross-talks? A suitable comment on the DWDM characterization is necessary. Mention the make of the DWDM and its transmission specifications.

13. What is a source meter? what is actually measured using it and how is it calibrated?

14. What was the maximum and minimum pump powers experimented for the long distance measurements?

15. In pages 10, 11:

i) What is the PM wavelength that was precisely kept in the experiment, to obtain the results of Fig. 1(d)?

- ii) what temperature is kept for these measurements in Figs. 2-b,c,e?
- iii) specify what lasers are used and their tunability range.
- iv) What are the details of this dispersion compensation module that is used? Specify any characterization graph measured to calibrate this.

16. What were the total channel losses in the deployed fiber (in dB), and how were they distributed?

17. PMD Compensation: The authors mention compensating for polarization mode dispersion (PMD) in the deployed fiber.

- How was the PMD characterized or quantified?
- What compensation technique was used?
- Was the compensation static or dynamically stabilized during operation?
- A sufficient study or characterization of the polarization drift and fluctuations in the deployed fiber is missing. Did the authors monitor the same during the course of the experiment? If not done, such a study is essential in this manuscript. It is suggested to detail the overall magnitude and timescale of polarization fluctuations observed in the deployed metro fiber. What specific stabilization or compensation technique was implemented to mitigate polarization drift during long-distance entanglement distribution?

Minor points:

- 18. In page 5, first line below Fig. 2: it is rather “spectral brightness” instead of “brightness”.
- 19. Page 8, line 8 from the top: type – “Bod” should be replaced by “Bob”.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have significantly improved the manuscript through their revisions, effectively addressing previous concerns. In particular, by carefully leveraging microheaters and a TEC to precisely locate the optimal operating point, the authors have successfully overcome the inherent limitations of the original design. Indeed, the inherent challenges in balanced brightness were major concerns in my previous review. Furthermore, the authors have clearly articulated the complementary nature of their scheme compared to previous architectures, and the high quality of the experimental results further validates the significance of this work. Given these improvements, I am happy to recommend this paper for publication in Nature Communications.

Reviewer #2

(Remarks to the Author)

I thank the authors for their detailed response and for providing data regarding the stability of the fiber links. This addition to the Supplementary Information is highly appreciated.

However, my original comment was aimed at assessing the long-term stability of the entire system, which includes also the integrated circuit. This is why I specifically requested data monitoring the pair generation rate and Bell state fidelity over time.

I want to emphasize that even if these stability numbers are not exceptional, it will not change my positive assessment of your work, in my opinion the paper absolutely merits publication. Nevertheless, because the manuscript places a strong focus on practical implementation and deployment readiness, it is important to provide the community with a transparent picture of the system's current overall stability.

Therefore, I kindly reiterate my request to include the data on long-term fidelity and pair generation rate.

Reviewer #3

(Remarks to the Author)

My concerns were satisfactorily addressed by the Authors and am happy to recommend publication.

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Responses to Reviewers' Comments

We greatly appreciate the reviewers' time and effort in reviewing our manuscript. The professional and insightful questions and comments have greatly helped us improve the work. Please find below our point-to-point responses and revisions in blue.

Response to Reviewer #1:

This study on TFLN-based integrated polarization-entangled photon source represents an interesting advancement in the fields of the TFLN integrated photonics. I think that the motivation of the work is meaningful and the long-distance multi-user quantum network experiment is interesting, though the experiment relies on the looped back scheme. The proposed devices rely on the co-linear two cascaded PPLNs with different phase matching types (i.e. type 0 and 1). While the authors strongly argue the advantages of the design in the manuscript, I think that such scheme inherently has many drawbacks. In addition, I believe that several experimental results may require additional explanations. As a result, I cannot recommend the publication of the current manuscript in Nature Communication.

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We thank the reviewer for the careful reading of our manuscript and for the constructive comments. We appreciate that the reviewer finds the motivation of the work meaningful and the multi-user quantum network experiment interesting. Below we address the reviewer's concerns point by point and have revised the manuscript to clarify several aspects of the device physics and experimental characterization.

Importantly, our intention in the manuscript was not to criticize previous approaches, but rather to present an alternative, distinct device architecture that directly generates polarization-entangled photon pairs on-chip through domain-engineered nonlinear interactions within a single waveguide. In practice, multiple approaches exist for generating polarization entanglement, each with its own advantages and design considerations. For example, in bulk optical systems, polarization-entangled photon sources have been realized using both collinear and non-collinear phase-matching configurations, including single-crystal single-pass, double-pass, and multi-crystal schemes [*Rev. Sci. Instrum.* **92**, 041101 (2021)]. These approaches represent different physical implementations of the same goal—generating high-quality polarization-entangled photon pairs.

Similarly, in integrated photonics, different device architectures can be developed to realize polarization entanglement. The goal of our work is to demonstrate a complementary on-chip approach in which polarization entanglement is generated directly through domain-engineered nonlinear interactions. We have revised the manuscript to clarify this positioning and to better emphasize that these different approaches should be viewed as

complementary rather than competing solutions.

1. Challenges in the brightness balance between TE- and TM- polarized biphotons: The authors control the length of the PPLNs for the balancing. I believe that the authors determine the ratio of the length of two PPLNs by the inverse ratio of the nonlinear tensor coefficients ($L_{\text{type0}}/L_{\text{type1}} \approx d_{31}/d_{33}$) and the authors somehow achieved (or argued) the maximally entangled states with the concurrence close to 1.

1a. However, it is very surprising to me because the measured brightness should be highly dependent on the polarization dependent losses for coupling and propagation. Also, Figure 2 clearly shows the polarization dependence. However, the authors achieved comparable brightness in Fig. 1d and Fig. 3. In addition to the Figure 2d, the authors should include the SHG intensity figures without normalization.

We thank the reviewer for raising the important point regarding brightness balancing. During the device design, the interaction lengths of the two PPLN sections are determined based on the inverse ratio of the effective nonlinear coupling parameters of the two SPDC processes, which provides an initial design condition for balancing the pair-generation rates.

In practical experiments, the detected brightness can indeed be influenced by polarization-dependent coupling and propagation losses. We have characterized these losses in our device around 1550 nm and obtained the following values: TE polarization coupling loss of approximately 5.4 dB/facet and TM polarization coupling loss of approximately 5.7 dB/facet, while the propagation losses are about 0.2 dB/cm for TE polarization and 0.3 dB/cm for TM polarization. These differences are relatively small and therefore jointly introduce a limited imbalance in the generated photon-pair brightness. Moreover, any residual mismatch between the two SPDC processes can be compensated through further thermal tuning of the phase-matching conditions of the two PPLN sections. By adjusting the device temperature and control the phase matching independently, the effective nonlinear interaction (SPDC) within the investigated bandwidth of the two processes can be balanced, resulting in comparable brightness. These losses may affect the heralding efficiency in the system, instead of the fidelity of the polarization entanglement. We have added these details in the revised manuscript.

Regarding the SHG measurements, Fig. 2a already reflects the intrinsic difference in nonlinear interaction strength between the two PPLN sections, while Fig. 2c and Fig. 2d are intended to illustrate the temperature-dependent phase-matching characteristics.

performances separately before evaluating polarization entanglement (Fig.3a, see Materials and Methods for experimental details). In practice, the pair generation rates from the two SPDC processes have initial difference, due to fabrication imperfections, such as thin-film thickness nonuniformity, waveguide linewidth variation, and waveguide losses. This imbalance can be compensated by thermally tuning the PM conditions of the two PPLN sections with independent microheaters. By adjusting the device temperature independently, the SPDC efficiency of the two processes can be fine tuned to achieve comparable photon-pair brightness within the investigated bandwidth (see details in Supplementary Information Fig.S2). We measure the pair generation rate and coincidence-to-accidental ratio (CAR) as

c. Experimental details for classical characterizations of D-QPM PPLN waveguide. We characterize the nonlinear performance of the device at room temperature. To extract the type-0 and type-I SHG conversion efficiencies, we first calibrate the fiber-to-chip coupling loss using lensed fibers, and the coupling losses are measured to be 5.4 dB per facet for TE polarization and 5.7 dB per facet for TM polarization around 1550 nm, and 8.7 dB per facet for TE polarization around 775 nm. The propagation loss is measured to be ~ 0.2 dB/cm and ~ 0.3 dB/cm for TE and TM polarizations around 1550 nm, respectively, and ~ 0.8 dB/cm for the TE polarization around 775 nm, based on the characterizations of microring resonators with the same dimension. Polarizations are aligned with a fiber polarization controller (PC)

1b. Furthermore, the authors assume the negligible loss of 775 nm mode. I think that it might not be very realistic because the PPLNs are often accompanied with the periodic grooves. Even without poling process, the waveguide might have a nonnegligible loss at 775 nm.

We thank the reviewer for raising this point. In the manuscript, we did not assume that the 775 nm pump mode has negligible loss. Instead, we experimentally characterized the propagation loss of the waveguide near 775 nm and obtained a value of approximately 0.8 dB/cm. The brightness mismatch induced by pump power differences can also be compensated by independent thermal tuning of the phase-matching conditions of the two PPLN waveguides. We have added the information in the revised manuscript.

In addition, we did not observe noticeable increase in propagation loss caused by the periodic poling. This conclusion is supported by measurements comparing poled and unpoled microring resonators fabricated on the same chip, which exhibit similar quality factors. This result indicates that the domain inversion process itself does not introduce significant additional scattering loss. Physically, domain inversion in lithium niobate corresponds to a reversal of the crystal polarization orientation within the unit cell and does not introduce structural discontinuities in the waveguide. Therefore, it does not inherently lead to optical scattering. Surface grooves sometimes observed in PPLN structures are typically associated with anisotropic wet etching/cleaning processes (e.g., HF or RCA solutions). In our fabrication process, such anisotropic chemical treatments were intentionally avoided, and therefore periodic grooves are not present in our devices.

c. Experimental details for classical characterizations of D-QPM PPLN waveguide. We characterize the nonlinear performance of the device at room temperature. To extract the type-0 and type-I SHG conversion efficiencies, we first calibrate the fiber-to-chip coupling loss using lensed fibers, and the coupling losses are measured to be 5.4 dB per facet for TE polarization and 5.7 dB per facet for TM polarization around 1550 nm, and 8.7 dB per facet for TE polarization around 775 nm. The propagation loss is measured to be ~ 0.2 dB/cm and ~ 0.3 dB/cm for TE and TM polarizations around 1550 nm, respectively, and ~ 0.8 dB/cm for the TE polarization around 775 nm, based on the characterizations of microring resonators with the same dimension. Polarizations are aligned with a fiber polarization controller (PC)

1c. More importantly, the proposed cascading scheme might be very challenging to employ the additional electrical control circuits of the pump intensity for the brightness compensation.

We thank the reviewer for raising this point. In our practical scheme, brightness balancing

does not rely on actively controlling the pump intensity of the two nonlinear processes. Instead, we compensate for any imbalance by thermally tuning the phase-matching conditions of the two PPLN waveguide sections. This leverages the fact that SPDC brightness strongly depends on phase-matching function. Detuning the optimal phase-matching point away from the pump wavelength can reduce the source brightness. By varying the individual device temperature by local microheaters, the SPDC count rates of the two PPLN sections can be tuned independently, allowing us to equalize the photon-pair generation rates within the investigated bandwidth without requiring additional electrical control circuits for pump power tuning.

1d. The authors should elaborate how they achieved comparable brightness for TETE and TMTM photon-pairs as shown in Fig. 1d.

We thank the reviewer for raising this point. Comparable brightness between the TE and TM photon-pair channels is achieved through a combination of device design and thermal tuning. During the device design stage, as recognized by the reviewer, the interaction lengths of the two PPLN sections are chosen according to the inverse ratio of the effective nonlinear coupling parameters of the two SPDC processes, which provides an initial balance of the pair-generation rates.

In the experiment, any practical imbalance arising from polarization-dependent coupling losses, propagation losses, or pump power differences is compensated by thermally tuning the phase-matching conditions of the two PPLN sections. We first set the TEC global temperature to 50 °C to shift type-I phase-matching wavelength to DWDM CH33 wavelength and roughly align with the type-0 phase-matching wavelength (Fig. 2d in the manuscript). By adjusting the type-0 PPLN temperature individually using microheater, the type-0 phase matching and its SPDC rate can be fine-tuned to achieve comparable photon-pair brightness as type-I SPDC within the investigated bandwidth of the DWDM, as can be seen in the following figure.

We have provided detailed explanations and added the balancing process in the revised manuscript.

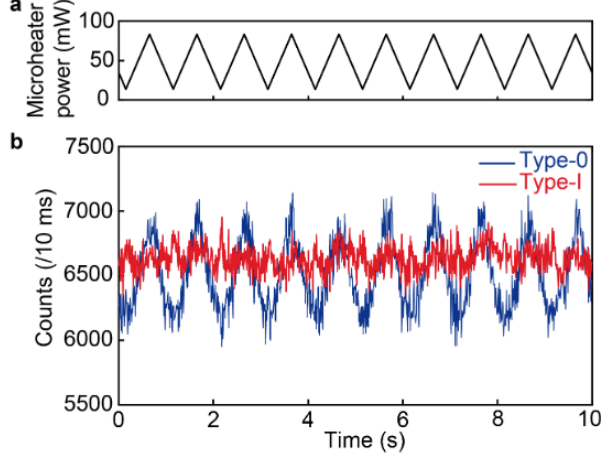


FIG. S2. **Type-0 and type-I SPDC photon count balancing using integrated microheater.** **a**, Applied electrical power with a periodic triangular waveform to the localized microheater on the type-0 PPLN nanophotonic waveguide. **b**, Type-0 (blue) and type-I (red) SPDC photon counts as a function of applied electrical power. While type-0 SPDC count rate is modulated, type-I count rate remains unaffected, indicating robust thermal control and negligible thermal crosstalk, respectively. Such localized thermal tuning enables balancing of type-0 and type-I photon count rates within the investigated bandwidth.

performances separately before evaluating polarization entanglement (Fig.3a, see Materials and Methods for experimental details). In practice, the pair generation rates from the two SPDC processes have initial difference, due to fabrication imperfections, such as thin-film thickness nonuniformity, waveguide linewidth variation, and waveguide losses. This imbalance can be compensated by thermally tuning the PM conditions of the two PPLN sections with independent microheaters. By adjusting the device temperature independently, the SPDC efficiency of the two processes can be fine tuned to achieve comparable photon-pair brightness within the investigated bandwidth (see details in Supplementary Information Fig.S2). We measure the pair generation rate and coincidence-to-accidental ratio (CAR) as

inputs. The polarization-dependent coupling losses and propagation losses are relatively small, thus jointly introducing a limited imbalance in the generated photon-pair brightness for type-0 and type-I SPDC. The minor brightness mismatch can be further compensated by independent thermal tuning of the two PPLN PM conditions. Experimentally, to balance the brightness, a 15 nm bandpass filter centered at 1550 nm is initially inserted, ensuring

equivalent collection of broad bandwidths. Each PBS output is further divided by a 50/50 beam splitter and detected by SNSPDs (IDQ ID281), with coincidences recorded on a time-to-digital converter (TDC). We heat up the global temperature to 50°C by TEC, roughly matching the PM wavelengths of the two PPLN waveguides and aligning the type-I PM wavelength to CH33 (1550.92 nm), and adjust the type-0 phase matching independently by fine tuning the power supply (Keithley 2230) power applied to the local microheater on the type-0 PPLN waveguide. The bandpass filter is then removed, and PBS outputs are

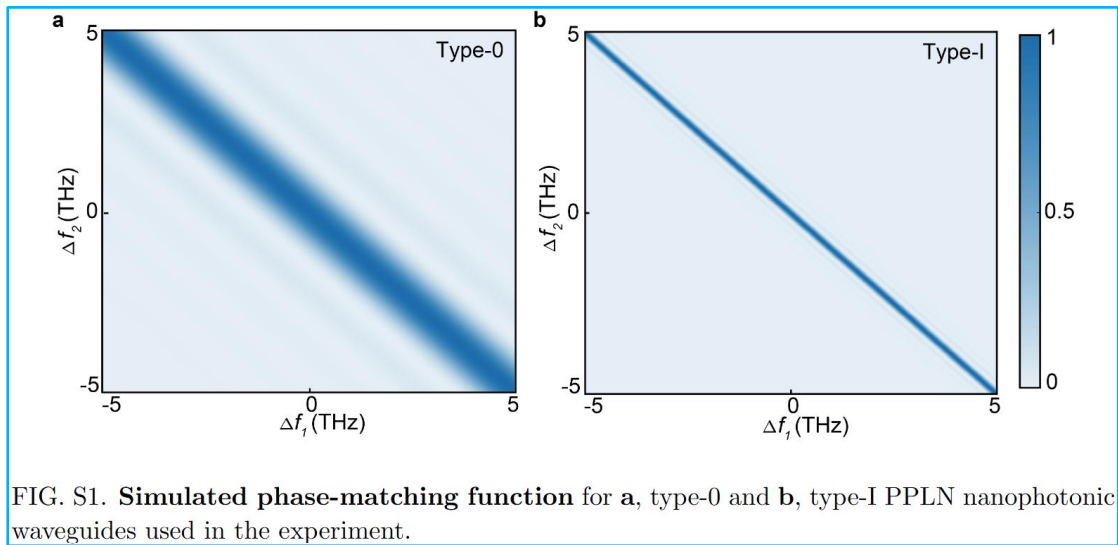
2. Bandwidth problems of two different phase matching conditions: The proposed scheme inherently has different frequency bandwidths for the TETE and TMTM biophoton states. Such problems can be found in Fig. 2d. Specifically, the bandwidth of the type 1 phase matching is smaller than that of type 0. Although SPDC often has broad bandwidths, it does not guarantee comparable brightness for broadband widths. Interestingly, the authors report the flat brightness for many DWDM channels in Fig. 3f and 3g. I think that the authors should elaborate how they achieve such responses.

We thank the reviewer for raising this important point. We would like to clarify that Fig. 2d shows the SHG spectra, which are used to determine the phase-matching wavelength for SHG process, but the SHG bandwidth does not represent the SPDC bandwidth.

For the SPDC process (which can be regarded as the reverse process of sum-frequency generation, SFG), the relevant bandwidth is determined by the broadband phase-matching response, which we experimentally characterize using SFG measurements, as shown in Fig. 2b and Fig. 2c (simulation is also attached in Supplementary). From the measurement results, the photon-pair bandwidths are ~ 78 nm for the type-0 SPDC process and ~ 51 nm for the type-I SPDC process.

In our wavelength-multiplexed entanglement experiment, the coincidence measurements shown in Fig. 3f and Fig. 3g are performed using DWDM channels ranging from CH17 (1563.86 nm) to CH49 (1538.19 nm), corresponding to a wavelength span of approximately 26 nm. This range is well within the measured phase-matching bandwidths of both nonlinear processes, which enables relatively uniform photon-pair generation rates across the measured channels.

We have clarified this point in the revised manuscript to better distinguish the SHG characterization used to identify phase-matching conditions from the SFG measurements used to determine the effective SPDC bandwidth.



b. Classical characterization of D-QPM PPLN waveguide. The device's classical performance is evaluated through second-harmonic generation (SHG) and sum-frequency generation (SFG) measurements. The SHG conversion efficiencies of the type-0 and type-I PPLN waveguides are obtained by continuous-wave (CW) pumping at their respective phase-matched FH wavelengths with TE and TM polarizations at room temperature, respectively (Fig.2a). The measured normalized conversion efficiencies are $56.5 \pm 0.8\% \text{ W}^{-1}$ for type-0 and $35.5 \pm 0.7\% \text{ W}^{-1}$ for type-I, with the difference attributed to fabrication imperfections such as variations in poling depth, duty cycle, and thin-film thickness. The PM characteristics are further examined via SFG measurements (Figs.2b, c; also see simulations in Supplementary Information Fig.S1). The anti-diagonal slopes of both PPLN follow the energy conservation line ($\Delta f_1 + \Delta f_2 = 0$), indicative of broadband SPDC. The inferred SPDC bandwidths from the SFG measurements are about 78 nm and 51 nm for the type-0 and type-I processes^{41,42}.

CH32 and CH49 to CH34) (Fig.3f, g). The JSI for type-0 and type-I SPDC shows flat pair generation rates across 16 telecom C-band channel pairs with <10% coincidence variation, thanks to the broadband PM conditions of both processes as shown in Fig.2b, c. The

3. Robustness characteristics of the PSRs: Many polarization components can support the robust broadband operations because one can readily design the components using the concept of adiabaticity. Practically, I think that optimization of two poling recipes is more challenging than the optimization of the high-performance polarization components.

We thank the reviewer for this insightful comment. We fully acknowledge the excellent works based on combining two type-0 PPLN sources with a multimode interference (MMI) beam splitter and an adiabatic polarization splitter-rotator (PSR) [*arXiv. 2506.23625 (2025)*; *Phys. Rev. Lett. 135, 250803 (2025)*]. Our work presents a different method. Both approaches offer viable routes toward integrated polarization-entangled photon sources, and each has its own advantages and limitations.

The PSR-based approach benefits from using the larger d_{33} nonlinear coefficient in both PPLN sections, yielding higher pair-generation efficiency. While polarization components such as PSRs can, in principle, be designed to operate robustly with broad bandwidth using adiabatic concepts, in practice, maintaining precise polarization control in TFLN nanophotonic waveguides can be challenging. This is mainly due to the slanted sidewalls and birefringence, as discussed in previous work [*Photonics 2024, 11(8), 771*] and also observed in our own experiments. Polarization-dependent losses in the PSR and modal dispersions in MMI beam splitters are also practical concerns, as discussed in the supplementary information of Ref. [*Phys. Rev. Lett. 135, 250803*].

The fabrication and poling processes for PPLN waveguides have been developed for many years in various research groups. Based on our experience, the processes for fabricating PPLN with slightly different poling periods (4.76 μm and 4.54 μm for type-0 and type-I phase matching, respectively) are essentially identical, with the only difference being the electrode period used for poling. In practice, fabrication imperfections and thin thickness variations can lead to some deviations in nonlinear efficiency between different PPLN waveguides, which will result in different brightness of the two sources.

Similar challenges also exist in architectures based on two independent type-0 PPLN

sources, where achieving identical phase-matching wavelengths and nonlinear interaction strengths on the same chip can likewise be difficult in practice [*Phys. Rev. Lett.* 134, 223602; *Phys. Rev. Lett.* 135, 250803 (Supplementary Information)]. In this context, the thermo-optic phase-matching tuning and photon-pair rate balancing strategy demonstrated in our work provides a practical and flexible approach for compensating fabrication-induced variations. We believe such active balancing and tuning capability could also be beneficial for the polarization-entanglement source based on two type-0 PPLNs.

Overall, both approaches involve practical trade-offs. The choice would depend on device design priorities, fabrication capabilities, and the specific expertise of the research groups. Our work aims to demonstrate the feasibility of the dual-QPM PPLN architecture as a complementary approach to integrated polarization-entangled photon sources.

We have rephrased the content to make this moderate and incorporated the advantages of the dual type-0 PPLN schemes.

bate (TFLN) via type-0 SPDC^{27–35}. These implementations typically rely on auxiliary polarization-handling components, such as polarization beam splitters, polarization rotators, two-dimensional gratings, and cross-polarized dual cavities, which may increase system complexity and constrain operational bandwidth. AlGaAs platform exploits both $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities to realize concurrent type-0 and type-I entanglement generation with high brightness, but they lack flexible and independent control over the two processes^{36–38}. Thus, despite significant progress, there remains strong interest in developing integrated polarization-entangled photon sources that are high-performance, controllable, and architecturally simple.

source throughout long-term measurements. Alternative integrated architectures based on two Type-0 PPLN sources can potentially achieve higher brightness by fully utilizing the largest d_{33} nonlinear coefficient. Such approaches provide another promising route toward integrated polarization-entangled photon sources^{34,35}.

4. Fidelity argument is not strictly fair: The authors argue 97~99 % fidelities without performing the full quantum state tomography. I think that the authors should perform the quantum state tomography if the authors want to argue the best performance in the paper. At least, the authors should rather show the fringes for R/L basis instead of the H/V basis. This is because the phase information between the HH and VV state is important and the QST experiment can confirm that the state is not the mixed state but the entangled state.

We thank the reviewer for this important comment. In our experiment, the polarization correlations were characterized in both the H/V and D/A bases. We would like to clarify that the D/A basis is equivalent to the R/L basis up to a unitary basis transformation, and therefore the measurements in the D/A bases already probe the relative phase coherence between the $|HH\rangle$ and $|VV\rangle$ components of the entangled state [*Science* 356.6343 (2017): 1140-1144, *Phys. Rev. Lett.* 75.24 (1995): 4337].

In particular, the two-photon interference fringes measured in the D/A basis directly verify the phase coherence between these two components, which distinguishes an entangled state from a classical mixed state. The high visibilities observed in both measurement bases therefore provide strong evidence of high-quality polarization entanglement.

We also note that our interference measurements were performed while continuously varying the relative phase, which provides a comprehensive characterization of the entangled-state coherence through the full interference fringe. In contrast, quantum state tomography typically reconstructs the density matrix from measurements at a finite set of discrete polarization settings. While tomography provides a complete state reconstruction, the continuously measured interference fringes directly reveal the phase coherence and stability of the generated entangled state.

Furthermore, the reported visibilities (97–99%) are calculated directly from the raw coincidence data without background subtraction, providing a conservative estimate of the entanglement quality. All reported fidelity values in our manuscript are calculated using a widely adopted approach in polarization entanglement experiments: $F=(1+V)/2$, where V is the average visibility measured in the rectilinear (H/V) and diagonal (D/A) bases, without subtracting accidental coincidences [*Optics express* 26.25 (2018): 32475-32490].

We have cited some compelling references in the revised manuscript to support our methodology.

channels (Fig.4c). Two representative channel pairs are randomly chosen for polarization-entanglement measurements: a far non-degenerate pair (CH21–CH45) and a near-degenerate pair (CH31–CH35) (Fig.1d), with respect to the degenerate wavelength corresponding to ITU channel CH33, which highlights the broadband operation of the source. For each channel pair, polarization correlations are measured in horizontal (H), vertical (V), diagonal (D), and anti-diagonal (A) bases^{7,17}. Two-fold coincidence for the two pairs is measured with raw visibilities of $V_{H/V} = 99.5 \pm 0.4\%$ and $V_{D/A} = 99.5 \pm 0.4\%$ for CH21–CH45, and $V_{H/V} = 97.8 \pm 1.2\%$ and $V_{D/A} = 99.5 \pm 0.4\%$ for CH31–CH35, without accidental subtraction. The results exhibit sinusoidal curves with clear constructive and destructive interferences, confirming strong quantum correlations between the signal and idler photons. The corresponding Bell-state fidelities are estimated to be $99.8 \pm 0.1\%$ and $99.3 \pm 0.3\%$, close to an ideal Bell state^{43,44}.

In summary, the quality of the multi-user quantum network experiment is fine. It is hard for me to agree with the strengths of the proposed device. Also, some results and arguments need supporting data or careful explanations. In addition, the wavelength multiplexing has been very widely employed in the quantum network, so it might not be very novel. Unless the authors provide strong advantages of the proposed device design, it might not be suitable for the publication in Nature communication.

We thank the reviewer for the careful evaluation of our work and for acknowledging the quality of the multi-user quantum network experiment. We appreciate the reviewer's request for a clearer presentation of the strengths and advantages of the proposed device architecture. In the revised manuscript, we have added additional explanations and supporting discussions to better highlight the key contributions of this work.

We would like to clarify that the main novelty of our work is not the use of wavelength multiplexing itself, which has indeed been widely employed in quantum communication systems. Instead, the key advance lies in the device architecture that directly generates polarization-entangled photon pairs on chip using dual quasi-phase-matched nonlinear interactions within a single TFLN nanophotonic waveguide. This approach enables:

1. **Direct on-chip generation of polarization-entangled photon pairs** without requiring interferometric stabilization or external polarization-manipulation circuits.
2. **Simultaneous phase-matching of two nonlinear processes within a single waveguide**, enabled by domain-engineered dual-QPM structures.
3. **Compatibility with wavelength-division multiplexing**, allowing a single integrated source to distribute entanglement to distant multiple users across many DWDM channels.
4. **Flexible reconfigurability of the nonlinear interactions**, which enables thermal tuning of the phase-matching wavelengths, balancing of the photon-pair brightness from the two types of SPDC processes, and adjustment of the relative phase between the $|HH\rangle$ and $|VV\rangle$ components of the entangled state.

Compared with previously reported integrated polarization-entangled photon sources, our work presents a new, competitive, but also complementary approach that is compact, phase-stable, and reconfigurable.

Response to Reviewer #2:

The manuscript presents an on-chip polarization-entangled photon-pair source based on Thin-Film Lithium Niobate (TFLN). The core of the paper lies in the implementation of dual quasi-phase matching, which allows for sequential Type-0 and Type-I spontaneous parametric down-conversion within a single nanophotonic waveguide. This architecture generates high-fidelity Bell states without the need for external tools. The authors successfully demonstrate the utility of this source through wavelength-multiplexed entanglement distribution in a four-user quantum network across up to 50 km of metropolitan fiber.

The paper is well-written and addresses a topic of broad interest to both technologists and scientists. The work is very timely, fitting well within the current trajectory of quantum communications. Technically, the study is sound; the Materials and Methods section is comprehensive and provides sufficient detail to reasonably allow for the reproducibility of the results. Additionally, the inclusion of a table comparing the results with the current state-of-the-art is highly appreciated and provides clear context for the device's performance. While this is not the first demonstration of integrated polarization entanglement, given that similar results were achieved in silicon years ago and a few works on TFLN have recently appeared on preprint servers (actually, Ref. 34 has been already published: <https://journals.aps.org/prl/abstract/10.1103/sfj2-dcx1>), the high performance of this specific implementation make it a valuable contribution to the field.

I recommend the paper for publication following minor modifications. In particular, I am curious to see data regarding the long-term stability of the main parameters, such as the pair generation rate and the fidelity of the generated Bell state. Furthermore, it would be highly beneficial if the authors could identify and discuss the physical origins of any observed instabilities. Providing these stability metrics would further support the claim of the source's readiness for practical deployment.

We are grateful for the reviewer's positive assessment of our work and for recognizing the significance of the device performance. We also appreciate the reviewer's suggestion to further clarify the stability of the system, which is indeed an important aspect for practical quantum communication applications.

First, we note that the deployed metropolitan fiber system used in this work is relatively stable and has been employed in several previous quantum communication measurements, where long-term operational stability has been demonstrated in previous systematic experiments [*Newton 1.10 (2025)*, *Applied Physics Letters 117.12 (2020)*]. In our current work, we further evaluated the stability of the experimental platform using classical characterization measurements, which are now included and discussed in the Supplementary Information (see the plots below). These measurements confirm the stable transmission and operation of the deployed fiber links.

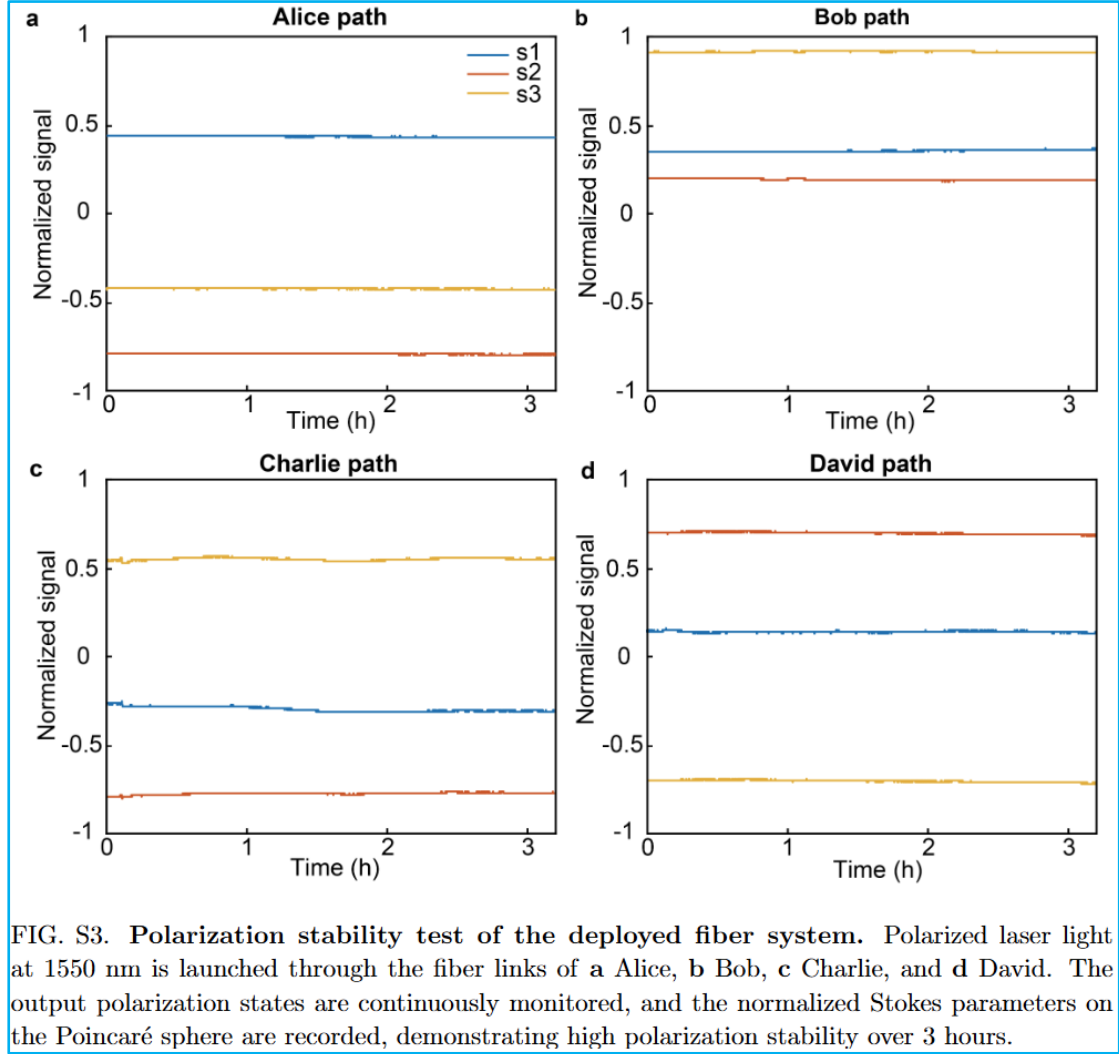


FIG. S3. **Polarization stability test of the deployed fiber system.** Polarized laser light at 1550 nm is launched through the fiber links of **a** Alice, **b** Bob, **c** Charlie, and **d** David. The output polarization states are continuously monitored, and the normalized Stokes parameters on the Poincaré sphere are recorded, demonstrating high polarization stability over 3 hours.

Meanwhile, implementing active polarization stabilization or advanced compensation strategies could further help to mitigate the polarization drift and maintain high-fidelity transmission over extended distances. Alternatively, narrowing the photon-pair spectral bandwidth, for instance, by employing microring resonators that generate ultra-bright, narrow-band photon pairs, can further suppress the impacts of both PMD and chromatic dispersion. These approaches will jointly help to enhance the system robustness and scalability for practical quantum network deployment.

Regarding potential sources of instability, the dominant factors in such experiments may typically include temperature fluctuations slightly affecting the phase-matching conditions of the nonlinear waveguide and fiber-chip coupling drift. In our system, these effects can be further mitigated through active monitoring the SPDC photon counts and output pump power, which allows us to compensate the drifts and maintain stable device operation throughout the measurements.

To address the reviewer's suggestion, we have added clarifications in the revised manuscript and Supplementary Information.

Additionally, we have also updated the cited reference information.

ties reported here represent conservative estimates of real-world performance. Although the deployed fiber links have been tested with high stability (see details in Supplementary Information Fig.S3), implementing active polarization stabilization or advanced compensation strategies would help to mitigate the PMD effect and maintain high-fidelity transmission over extended distances for long-term operation⁶². Alternatively, narrowing the photon-pair spectral bandwidth, for instance, by employing microring resonators that generate ultra-bright, narrow-band photon pairs, can further suppress the impacts of both PMD and chromatic dispersion⁵³. These approaches will collectively enhance the system robustness and scalability for practical quantum network deployment.

numerical-aperture fibers, could reduce this bottleneck^{58–60}. Active monitoring on both types

of SPDC pair generation rates and output pump power would further enable compensation of temperature fluctuations and coupling drifts, helping to maintain stable operation of the source throughout long-term measurements. Alternative integrated architectures based on two Type-0 PPLN sources can potentially achieve higher brightness by fully utilizing the largest d_{33} nonlinear coefficient. Such approaches provide another promising route toward integrated polarization-entangled photon sources^{34,35}.

Response to Reviewer #3:

The authors have demonstrated a telecom polarization-entangled photon-pair source on thin-film lithium niobate (TFLN) employing dual quasi-phase matching in a single nanowaveguide, eliminating the need for interferometers, etc. while directly producing high-fidelity Bell states. Using this, they realized WDM-based entanglement distribution in a four-user quantum network deployed over metropolitan fiber links up to 50 km, without active time synchronization.

We thank the reviewer for providing valuable suggestions to help us improve the manuscript.

Here are some critical points/comments and suggestions:

1. In the network demonstration, a loopback configuration is used, effectively doubling the optical path length between the nodes. Does this imply that no active time synchronization of the time-stamper clocks was required between the user pairs? For a practical implementation consisting of users at distant location, time synchronization of their clocks is imperative. This is somehow not clear in the manuscript, and therefore the authors are suggested to clarify this and also highlight this in the abstract, to avoid any misconception.

We thank the reviewer for raising this important point and for the suggestion to clarify the description of the network experiment.

As correctly pointed out by the reviewer, our current experiment uses a loopback configuration, where all photons are ultimately detected using SNSPDs connected to a single time tagger. It therefore does not involve synchronization between spatially separated and independently clocked time-stamping units. We agree with the reviewer that in a practical deployment with users located at distant sites, synchronization between independent time-stamping systems is essential.

We note that implementing a fully distributed architecture with independent detectors and synchronized time-stamping systems at each node is an important next step toward practical quantum networks. Our current loopback demonstration emulates a distributed scenario in which photons experience realistic transmission losses and environmental perturbations (e.g., polarization drift and dispersion) associated with deployed fiber networks. It is commonly adopted in entanglement distribution experiments to validate transmission performance while maintaining a centralized detection system (*Nature Communications* 15, 1651 (2024), *Science Advances* 6.36 eaba095 (2020), *Optica* 12, 570-576 (2025)). It allows us to isolate and validate the performance of the entanglement source and transmission channels without introducing additional complexity from synchronization hardware.

To avoid potential misunderstanding, we have clarified this point in the revised manuscript and highlighted the role and limitation of the loopback configuration.

ization rotators, or other complex circuits. The source directly produces high-fidelity Bell states with broad bandwidth, high brightness, and low noise. Using this integrated platform, we realize wavelength-multiplexed entanglement distribution in a four-user quantum network deployed over a loop-back metropolitan fiber links up to 50 km. These results establish a robust and scalable pathway toward practical quantum communication systems and multi-user quantum mesh networks based on integrated photonics.

lie, and David (Fig.4b), according to the communication layer (Fig.4d). Each path is then looped back for polarization analysis and detection without active time synchronization.

2. In the four-user configuration (Alice, Bob, Charlie, and David), are all users interconnected with each other simultaneously (i.e., a fully connected network)? Or are only two users connected at a time, with entanglement distributed to a selected pair?

We thank the reviewer for this question and the opportunity to clarify the network configuration.

In the four-user configuration (Alice, Bob, Charlie, and David), entanglement distribution is implemented via paired connections, where two pairs (4 users) are connected simultaneously through wavelength multiplexing. Specifically, three pairing configurations are realized: Alice–Bob with Charlie–David, Alice–Charlie with Bob–David, and Alice–David with Bob–Charlie.

Due to the limited number of available single-photon detectors in the current setup, the polarization-entanglement characterization is performed for one user pair at a time, although the corresponding wavelength channels for multiple pairings are simultaneously present in the system.

Leveraging the broadband nature of our source enables the use of multiple DWDM channels across the telecom C-band, which in principle allows simultaneous entanglement distribution among multiple user pairs. Realizing a fully connected quantum network with independent detectors and synchronized time-stamping systems at each node, rather than the current loopback configuration, is an important next step toward a fully functional quantum mesh network.

We have clarified this point in the revised manuscript.

Our current network demonstration distributes entanglement among four nodes using two pairs of wavelength channels. Due to the limited number of SNSPDs in the current

experimental setup, characterization is performed for one user pair at a time, though the wavelength channels for all pairs are simultaneously present in the system. Leveraging the broadband operation of our polarization-entangled photon-pair source (Fig.3f, g) would allow full utilization of available DWDM channels across the telecom C-band, supporting simultaneous entanglement distribution among more users. Implementing a fully distributed architecture with independent detectors and synchronized time-stamping systems at each node, rather than the looped-back scheme, is an important next step toward achieving a fully functional quantum mesh network, in which independent users can simultaneously share and verify entanglement across the network⁶³.

3. There's a huge literature pertaining to the efficient generation of polarization-entangled photon pairs, in ppLN crystals and waveguides. The review done in this paper is still insufficient. For example, quantum sources for the generation of efficient, fully guided-wave, compact and multiuser polarization-entangled photon pairs have a substantial background literature.

(i) In this connection the current manuscript, its characterizations, results and inferences, etc. are very similar to the work done in the following references and, therefore, requires to be properly cited:

Telecom source of tunable polarization-entanglement distribution up to 100 km for multi-user QKD over metro-area fiber-optic networks. APL Quantum, 2, 016102 (2025).

(ii) Additionally, since the polarization-entanglement generation approach is based on multiple periodic poling, it may be appropriate to include earlier theoretical work in this context. One example where this detail analysis of keeping different poling lengths for the Type-0 and Type-1 regions, while equating the respective SHG efficiencies can be found from the following reference:

Generation of two different polarization-entangled biphoton states in a potassium titanyl phosphate waveguide device with multiple periodic poling, Phys. Rev. A 101, 023832 (2020).

Including this work could help contextualize and compare your technique with similar multiple-poling approaches reported in integrated nonlinear platforms.

We thank the reviewer for highlighting these important references and for suggesting improvements to the literature review.

(i) We agree that there is a substantial body of work on guided-wave polarization-entangled photon sources and multi-user entanglement distribution in fiber networks. Following the reviewer's suggestion, we have now included and cited the work reported in APL Quantum 2, 016102 (2025) in the revised manuscript. This study demonstrates an efficient guided-wave polarization-entangled photon source and its application to long-distance

entanglement distribution. We have added this reference in the Introduction to better position our work within the broader context of SPDC entangled-photon sources and multi-user quantum communication systems.

(ii) We also appreciate the reviewer's suggestion to include earlier theoretical work on multiple periodic poling for polarization-entanglement generation. The work reported in Phys. Rev. A 101, 023832 (2020) provides an important theoretical analysis of multi-region periodically poled nonlinear waveguides for generating polarization-entangled photon pairs. We have now cited and discussed this reference in the manuscript to better contextualize our device design.

We have added these references in the revised manuscripts.

communication to quantum computing¹. Among various forms of entanglement, polarization entanglement plays a central role due to its straightforward state manipulation for direct applications in emerging quantum technologies, such as machine learning on a quantum computer, device-independent quantum key distribution, quantum teleportation, and quantum-enhanced bioimaging²⁻¹⁵.

periods (Fig.1a). Similar concept has been theoretically proposed in potassium titanyl phosphate (PPKTP) crystal³⁹. In type-0 SPDC, a transverse-electric (TE) pump photon

More Technical points:

4. In general, the quality of the figures require improvement as their resolution, contrast and clarity are quite poor.

In Fig. 1a, the optical micrograph of the fabricated D-QPM ppLN is not clear. Also, Fig. 1c,(ii) is not clear at all.

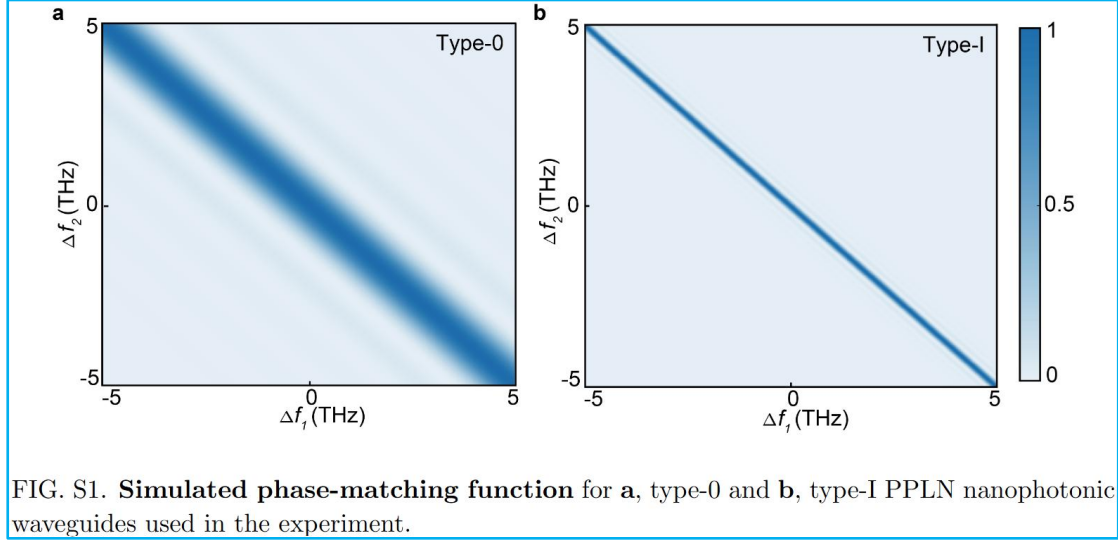
The resolution of Figs. 2 and 3 also seems poor. The authors are suggested to use a better software for plotting their figures or at least replace them with the original figures of better resolution.

Figures do not appear very clear. In Figs. 2 a, d, e, usage of Darker fonts is suggested. Also, in Figs. b and c the resolution needs to be improved. A calculated spectra corresponding to wavelength detuning could also be inserted as an inset in each figure.

We thank the reviewer for these suggestions regarding the figure quality. All figures in the manuscript are originally generated as vector graphics with high resolution in the submitted files. We have checked and re-exported all figures using higher-resolution settings to improve readability. It is also noted that Fig.1a and 1c(ii) are raw microscope and scanning electron microscope images, respectively, and the resolution and contrast are set by the equipment. Figs. 2b and c are also plotted with raw measured results, and the pixel resolution is limited by the sweeping step of the tunable laser. All fonts are colored by black, dark blue and dark red, and we have increased font size to the plot clear. We will also submit vector graphics separately for publishing purpose.

Regarding the reviewer's suggestion of including calculated spectra as an inset, we appreciate the suggestion. The purpose of the current figures is to present the experimentally measured spectra, which directly characterize the device performance. To

maintain clarity and avoid overcrowding the figures, we have chosen to add the simulation results in the Supplementary.



5. How are the three microheaters tuned/controlled for controlling their phase-matching wavelengths and relative phases? How does one ensure that these introduce only local heating, while the neighboring portion remains unaffected? This is crucial and some measurement pertaining to the same is mandatory. Why is any possibility for the transport of heat to slightly neighboring regions ruled out? Is there any earlier study related to the same effect?

We thank the reviewer for raising this point regarding the thermal control of the device.

In our experiments, after aligning the phase-matching wavelength of the two PPLN by global heater (temperature-controlled sample mount), we further balance their SPDC brightness by applying electrical power to the local microheaters. The localized microheater is to fine tuning the phase-matching condition individually to balance the two SPDC processes, so the induced temperature change is relatively small, and the thermal influence on neighboring regions is minimal. This is also experimentally verified. We tune the electrical power applied onto the microheater on type-0 PPLN waveguide, to make its SPDC photon counts equivalent to the type-I SPDC photon counts. As can be seen in the following figure, while the type-0 SPDC photon counts are modulated, the type-I counts remain unaffected noticeable correlations to the type-0 SPDC rates, indicating negligible thermal crosstalk.

Thermal tuning using localized microheaters is a well-established technique in integrated photonic platforms [*Nature Photonics* 11.7 (2017): 447-452, *Science* 349.6249 (2015): 711-716], where the relatively small heated region and moderate temperature changes allow effective local control while maintaining stable operation of adjacent structures with negligible thermal crosstalk. Our microheaters are separated by $>100\text{ }\mu\text{m}$, and we do not observe obvious crosstalk issue. To clarify these points, we have expanded the description of the thermal tuning scheme and added experimental verifications in the revised manuscript.

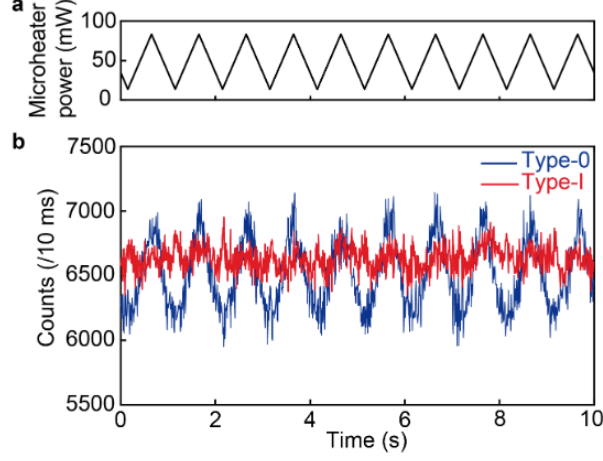


FIG. S2. Type-0 and type-I SPDC photon count balancing using integrated microheater. **a**, Applied electrical power with a periodic triangular waveform to the localized microheater on the type-0 PPLN nanophotonic waveguide. **b**, Type-0 (blue) and type-I (red) SPDC photon counts as a function of applied electrical power. While type-0 SPDC count rate is modulated, type-I count rate remains unaffected, indicating robust thermal control and negligible thermal crosstalk, respectively. Such localized thermal tuning enables balancing of type-0 and type-I photon count rates within the investigated bandwidth.

performances separately before evaluating polarization entanglement (Fig.3a, see Materials and Methods for experimental details). In practice, the pair generation rates from the two SPDC processes have initial difference, due to fabrication imperfections, such as thin-film thickness nonuniformity, waveguide linewidth variation, and waveguide losses. This imbalance can be compensated by thermally tuning the PM conditions of the two PPLN sections with independent microheaters. By adjusting the device temperature independently, the SPDC efficiency of the two processes can be fine tuned to achieve comparable photon-pair brightness within the investigated bandwidth (see details in Supplementary Information Fig.S2). We measure the pair generation rate and coincidence-to-accidental ratio (CAR) as

inputs. The polarization-dependent coupling losses and propagation losses are relatively small, thus jointly introducing a limited imbalance in the generated photon-pair brightness for type-0 and type-I SPDC. The minor brightness mismatch can be further compensated by independent thermal tuning of the two PPLN PM conditions. Experimentally, to balance the brightness, a 15 nm bandpass filter centered at 1550 nm is initially inserted, ensuring

equivalent collection of broad bandwidths. Each PBS output is further divided by a 50/50 beam splitter and detected by SNSPDs (IDQ ID281), with coincidences recorded on a time-to-digital converter (TDC). We heat up the global temperature to 50°C by TEC, roughly matching the PM wavelengths of the two PPLN waveguides and aligning the type-I PM wavelength to CH33 (1550.92 nm), and adjust the type-0 phase matching independently by fine tuning the power supply (Keithley 2230) power applied to the local microheater on the type-0 PPLN waveguide. The bandpass filter is then removed, and PBS outputs are routed through a DWDM module (FS TECH PTE. LTD., see transmission in Supplementary Information Fig.S4) to select channel pairs (CH21–CH45) for individual type-0 and type-I JSI measurements (Fig.3a(iii)). Coincidence countings (Fig.3b, c, f, g) are measured

6. The ppLN regions are sub-centimeter lengths. It was unclear What is the reason for measuring such high SHG and SPDC efficiencies? An SHG efficiency of ~56% from a 1-cm long TFLN region, given the nonlinear efficiencies of the two TFLN regions were the usual QPM d_{eff} depending on the d_{33} and d_{31} coefficients of LN, seems overestimated? Is it any different from a (similarly fiber-pigtailed) ppLN waveguide of the same poling period but usually of longer length that corresponds to similar SHG efficiencies? A comparison is suggested.

Did the authors also perform a temperature scan of the SHG power, showing the sinc² behavior? Generally, the conversion efficiency changes with the input FH pump power. Was this noticed in the measurements? How was this incorporated while calculating the normalized SHG efficiencies?

We thank the reviewer for raising these questions regarding the nonlinear conversion efficiency and the SHG characterization.

First, we would like to clarify that the reported value is the normalized SHG efficiency of 56%/W, measured from a 1.2 mm long type-0 PPLN nanophotonic waveguide, rather than a 1-cm-long device. Such performance is consistent with previously reported results in thin-film lithium niobate (TFLN) nanophotonic waveguides, where strong optical confinement significantly enhances the nonlinear interaction. For example, normalized SHG efficiencies exceeding 500%/W have been reported in PPLN nanophotonic waveguides in many prior studies [*Photonics Research* 12, 1703–1708 (2024); *Applied Physics Letters* 116.10 (2020); *Opt. Express* 28, 19669–19682 (2020)]. Compared with conventional fiber-pigtailed PPLN waveguides in bulk crystals with larger mode sizes, the submicrometer cross-section of TFLN nanophotonic waveguides enables much tighter optical confinement and therefore

stronger effective nonlinear interaction. The theoretical analysis underlying this enhancement is discussed in Materials and Methods, a Device design.

We characterize the SHG spectrum by scanning the pump laser wavelength instead of varying the temperature. Fig. 2d presents the measured SHG spectra at various temperature, which characterizes the temperature-dependent phase-matching behavior. The measured spectra do not perfectly follow an ideal sinc^2 profile predicted by theory, which we attribute primarily to fabrication imperfections, such as small variations in the thin-film thickness along the waveguide. Such deviations from the ideal sinc^2 shape are commonly observed in nanophotonic nonlinear waveguides [*Laser Photonics Rev* 18, 2301128 (2024); *Opt. Express* 25, 6963-6973 (2017); *Applied Physics Letters* 116.10 (2020)].

We also confirm that the SHG conversion efficiency depends on the input fundamental pump power. In the manuscript, rather than directly plotting the conversion efficiency, we present the measured SHG output power as a function of the fundamental pump power in Fig. 2a. As expected for the undepleted pump regime, the SHG power scales quadratically with the pump power, while the conversion efficiency scales linearly with pump power, meaning that both representations provide equivalent information about the nonlinear interaction strength. At high pump power, SHG conversion efficiency will saturate, but we do not intend to access that regime for SPDC applications. To quantitatively compare the nonlinear performance of the two PPLN sections, we calculate the normalized SHG efficiency, which removes the dependence on pump power and allows a direct comparison of the intrinsic nonlinearity. This theory has been well studied and applied to characterize the SHG process [*Optica* 5.11 (2018): 1438-1441; *Photonics Research* 12, 1703–1708 (2024); *Applied Physics Letters* 116.10 (2020); *Opt. Express* 28, 19669-19682 (2020)].

7. The entangled coincidence rate is quite low as evident from Fig. 1d although the raw coincidences and CAR are pretty good. What are the various losses and/or transmission efficiencies considered and how are they incorporated in the calculation of their source brightness, in particular to the Type-0 and Type-1 TFLN regions? Are they over-estimating the losses?

We thank the reviewer for raising this question regarding the estimation of the source brightness.

We have characterized the fiber-to-chip losses and the propagation losses. The coupling losses are measured to be 5.4 dB per facet for TE polarization and 5.7 dB per facet for TM polarization around 1550 nm, and 8.7 dB per facet for TE polarization around 775 nm. The propagation loss is measured to be ~ 0.2 dB/cm and ~ 0.3 dB/cm for TE and TM polarizations around 1550 nm, respectively, and ~ 0.8 dB/cm for the TE polarization around 775 nm. The information is added in Methods.

During the coincidence measurements, we simultaneously recorded the single count rates at both detection channels in addition to the coincidence counts. The on-chip photon-pair generation rate is estimated using the relation $R_{\text{pair}} = (S_s S_i)/C$, where S_s and S_i are the measured single count rates of the signal and idler photons, and C is the coincidence

count rate [*Physical Review Letters* 125.26 (2020): 263602; *Physical Review Letters* 133.8 (2024): 083803].

This method allows us to directly infer the internal pair generation rate without explicitly summing individual losses in the optical paths. The losses are inherently reflected in the measured single and coincidence counts, and therefore are naturally taken into account in the estimation. As a result, this approach avoids uncertainties associated with separately estimating each loss component. The same procedure is applied when evaluating the photon-pair generation rates from both the type-0 and type-I PPLN, ensuring a consistent comparison of their brightness.

We have clarified this point in the revised manuscript.

c. Experimental details for classical characterizations of D-QPM PPLN waveguide. We characterize the nonlinear performance of the device at room temperature. To extract the type-0 and type-I SHG conversion efficiencies, we first calibrate the fiber-to-chip coupling loss using lensed fibers, and the coupling losses are measured to be 5.4 dB per facet for TE polarization and 5.7 dB per facet for TM polarization around 1550 nm, and 8.7 dB per facet for TE polarization around 775 nm. The propagation loss is measured to be ~ 0.2 dB/cm and ~ 0.3 dB/cm for TE and TM polarizations around 1550 nm, respectively, and ~ 0.8 dB/cm for the TE polarization around 775 nm, based on the characterizations of microring resonators with the same dimension. Polarizations are aligned with a fiber polarization controller (PC)

using these setups. The on-chip photon-pair generation rate is estimated using the relation $PGR = (S_s S_i)/C$, where S_s and S_i are the measured single count rates of the signal and idler photons, and C is the measured coincidence count rate. For heralded second-order

8. The phase-matching conditions and corresponding temperatures (PMT) are not mentioned clearly although the poling periods of the two regions are mentioned. The SHG experiments are performed at room temperature but their PMTs corresponding to the phase-matching condition are unclear. The authors are suggested to clearly provide the phase-matching temperature and corresponding pump wavelength required for degenerate SPDC in both Type-0 and Type-I configurations in the TFLN platform.

We thank the reviewer for raising this point and appreciate the opportunity to clarify the phase-matching conditions.

When doing the simulation, we assume the quasi-phase matching between 1550 nm and 775 nm at room temperature. However, due to fabrication imperfection, the phase-matching conditions are shifted. It can be compensated by thermal tuning. Thus, we investigate the thermal responses.

The temperature-dependent phase-matching behavior of the two PPLN is experimentally characterized in Fig. 2d, where the SHG spectra are measured as a function of the global chip temperature. This measurement shows the shift of the phase-matching wavelength for both the type-0 and type-I processes with temperature. In addition, Fig. 2e presents the phase-matching tuning induced by the local microheaters, which enables fine adjustment of the phase-matching wavelengths individually.

During the polarization entanglement measurements, the global chip heater is set to

50 °C, which approximately aligns the phase-matching wavelengths of the two nonlinear processes. **The local microheaters with an applied power around 50 mW** are then used for fine tuning of the phase-matching conditions to balance the photon-pair generation rates from the Type-0 and Type-I SPDC processes.

The pump wavelength for SPDC is fixed at **775.46 nm**, corresponding to DWDM channel CH33 at the fundamental wavelength. It is also noted that SPDC has a broad spectrum over 50 nm (as predicted by the SFG measurement in Fig.2b,2c) and what we selected from DWDM for investigation are basically non-degenerate photon pairs.

We have added these details in the revised manuscripts.

The deviation in observed PM wavelengths from the design and the non-ideal SHG spectra are mainly attributed to the fabrication imperfections. To compensate for the phase match-

to-digital converter (TDC). We heat up the global temperature to 50°C by TEC, roughly matching the PM wavelengths of the two PPLN waveguides and aligning the type-I PM wavelength to CH33 (1550.92 nm), and adjust the type-0 phase matching independently by fine tuning the power supply (Keithley 2230) power applied to the local microheater on the type-0 PPLN waveguide. The bandpass filter is then removed, and PBS outputs are

entangled photon-pair preparation. A tunable CW laser (Newport TLB-6712 Velocity) at 775.46 nm, corresponding to ITU channel CH33 at its FH wavelength, is used as the pump.

9. What's the emission bandwidth of the photon pairs in the respective Type-0 and Type-1 regions? Did the authors try to extract any information about the marginal spectra? Did the authors try to measure the resultant emission bandwidth of the photon pairs resulting from the device? The authors should quantify how much they actually imply when they mention "Far non-degenerate" and "near-degenerate".

We thank the reviewer for raising this point regarding the emission bandwidth of the photon pairs.

Unfortunately, we are not able to directly measure the full SPDC bandwidth, because it is too weak to measure with optical spectrum analyzer, and our DWDM only covering telecom C band is not broad enough. However, the SPDC bandwidth can be estimated by the phase-matching bandwidth. To characterize this, we performed sum-frequency generation (SFG) measurements for both the type-0 and type-I PPLN sections in the device, as shown in Fig. 2b and Fig. 2c. Multiplying this SFG phase-matching response with the pump envelope that dictates energy conservation gives the SPDC bandwidth [*Opt. Express* **28**, 38993-39004 (2020); *Light: Science & Applications* **7**, 17143 (2018)]. Based on these measurements, we estimate photon-pair bandwidths of approximately 78 nm for the Type-0 SPDC process and 51 nm for the Type-I SPDC process.

In the wavelength-multiplexed entanglement experiment, the coincidence measurements shown in Fig. 3f and Fig. 3g are performed using DWDM channels ranging from CH17 (1563.86 nm) to CH49 (1538.19 nm), corresponding to a total wavelength span of approximately 26 nm. This span lies well within the measured phase-matching bandwidths of both nonlinear processes, enabling relatively uniform photon-pair generation rates

across the multiplexed channels.

In the manuscript, the terms “near-degenerate” and “far non-degenerate” refer to the relative positions of the signal and idler channels with respect to the degenerate wavelength (twice as the pump wavelength), corresponding to ITU channel CH33. Specifically, near-degenerate channels correspond to CH31 and CH35, which lie close to the degenerate wavelength, while far non-degenerate channels correspond to CH21 and CH45, which are located further away from the degenerate point. These channel selections are used to demonstrate that the polarization-entangled photon source maintains good performance over the investigated spectral range.

We have clarified these points in the revised manuscript.

such as variations in poling depth, duty cycle, and thin-film thickness. The PM characteristics are further examined via SFG measurements (Figs.2b, c; also see simulations in Supplementary Information Fig.S1). The anti-diagonal slopes of both PPLN follow the energy conservation line ($\Delta f_1 + \Delta f_2 = 0$), indicative of broadband SPDC. The inferred SPDC bandwidths from the SFG measurements are about 78 nm and 51 nm for the type-0 and type-I processes^{41,42}.

channels (Fig.4c). Two representative channel pairs are randomly chosen for polarization-entanglement measurements: a far non-degenerate pair (CH21–CH45) and a near-degenerate pair (CH31–CH35) (Fig.1d), with respect to the degenerate wavelength corresponding to ITU channel CH33, which highlights the broadband operation of the source. For each chan-

10. What was the pump power kept for these measurements? Not much details are mentioned about the type and make of the pump laser/source in the various experiments (except at one place, about the Santec TSL-570), wavelength, linewidth of the pump that drives the SPDC processes in the D-QPM TFLN regions. Are SNSPD detectors used for all the experiments? In order to rule out any distinguishability between the photons from the different QPM processes, what was the pump wavelength that was ultimately maintained and how was that deciphered?

We thank the reviewer for pointing out the need for clearer experimental details.

In the polarization-entanglement measurements, the device is pumped by a continuous-wave laser (Newport TLB-6712 Velocity) at a wavelength of 775.46 nm, corresponding to the degenerate SPDC condition for ITU channel CH33. We obtain orthogonal polarized photon pair rate by separating them using polarization beam splitter for detection. To balance the SPDC rates, we thermally tune the phase matching wavelengths of the two PPLN independently to make them align around the pump wavelength and. The pump laser has a narrow linewidth of <200 kHz, which corresponds to a coherence length much longer than the spatial separation between the two PPLN sections in the device. As a result, the photon pairs generated from the two quasi-phase-matched regions remain indistinguishable with respect to the pump coherence, enabling the coherent superposition required for polarization entanglement. The on-chip pump power is kept at -2 dBm for the measurements in Fig. 4.

All quantum measurements reported in this work are performed using superconducting

nanowire single-photon detectors (SNSPDs, IDQ-ID281), as shown in each measurement setup schematic.

We have added these details in the revised manuscript.

detection, to compensate for the accumulated dispersion of $\sim 650 \text{ ps nm}^{-1}$. The on-chip pump power is kept at -2 dBm during the measurement.

entangled photon-pair preparation. A tunable CW laser (Newport TLB-6712 Velocity) at 775.46 nm, corresponding to ITU channel CH33 at its FH wavelength, is used as the pump. The pump laser has a linewidth of <200 kHz, corresponding to a coherence length much longer than the spatial separation between the two PPLN sections, which make the photon pairs generated from the two quasi-phase-matched regions remain indistinguishable with respect to the pump coherence. The pump is coupled into optical fiber via a collimator, with

11. In page 4, what is this ultimate PMT kept for the two ppLN regions? What are the exact roles of the TEC module and the integrated microheaters in achieving the highest visibilities in the TPA that correspond to high entanglement fidelity along with a substantial rate of coincidences?

We thank the reviewer for raising this question regarding the thermal control scheme used in the experiment.

In the experimental, we use the thermal tuning to balance the pair generation rate of the two SPDC process. The global chip temperature is stabilized using a thermoelectric cooler (TEC), and is used for roughly align the phase-matching wavelength of the two PPLN sections. The TEC is set to **50 °C during** the measurement.

The integrated microheaters, located above the individual PPLN sections, are then used for local fine tuning. By adjusting the local temperature of each nonlinear section, we can precisely balance the photon-pair generation rates of the Type-0 and Type-I SPDC processes (see Supplementary Fig. S2).

The microheater in between the two PPLN waveguide is able to thermally tune the phase difference between the two SPDC sources. The polarization-entangled state at the waveguide output can be expressed as $|\psi\rangle = \alpha|H_s H_i\rangle + \beta e^{i\phi}|V_s V_i\rangle$, where α and β are the probability amplitudes, that is the pair generation rate, of the two SPDC processes, and ϕ represents their relative phase. Maximal entanglement is obtained when $\alpha=\beta$ and $\phi=0$ or π , yielding $|\psi_{max}\rangle = \frac{1}{\sqrt{2}}(|H_s H_i\rangle \pm |V_s V_i\rangle)$. This directly determines the entanglement fidelity of the source.

We have clarified this point in the revised manuscript.

and Methods for experimental details). In practice, the pair generation rates from the two SPDC processes have initial difference, due to fabrication imperfections, such as thin-film thickness nonuniformity, waveguide linewidth variation, and waveguide losses. This imbalance can be compensated by thermally tuning the PM conditions of the two PPLN sections with independent microheaters. By adjusting the device temperature independently, the SPDC efficiency of the two processes can be fine tuned to achieve comparable photon-pair brightness within the investigated bandwidth (see details in Supplementary Information Fig.S2). We measure the pair generation rate and coincidence-to-accidental ratio (CAR) as

independent thermal tuning of the two PPLN PM conditions. Experimentally, to balance the brightness, a 15 nm bandpass filter centered at 1550 nm is initially inserted, ensuring

equivalent collection of broad bandwidths. Each PBS output is further divided by a 50/50 beam splitter and detected by SNSPDs (IDQ ID281), with coincidences recorded on a time-to-digital converter (TDC). We heat up the global temperature to 50°C by TEC, roughly matching the PM wavelengths of the two PPLN waveguides and aligning the type-I PM wavelength to CH33 (1550.92 nm), and adjust the type-0 phase matching independently by fine tuning the power supply (Keithley 2230) power applied to the local microheater on the type-0 PPLN waveguide. The bandpass filter is then removed, and PBS outputs are

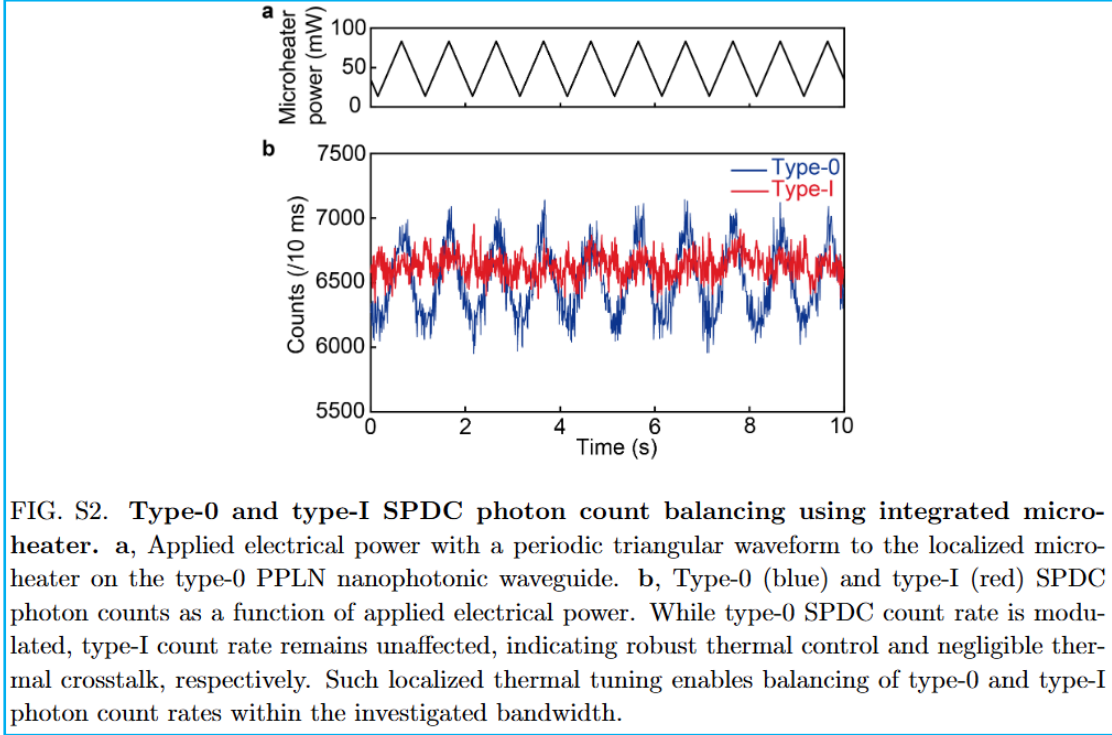
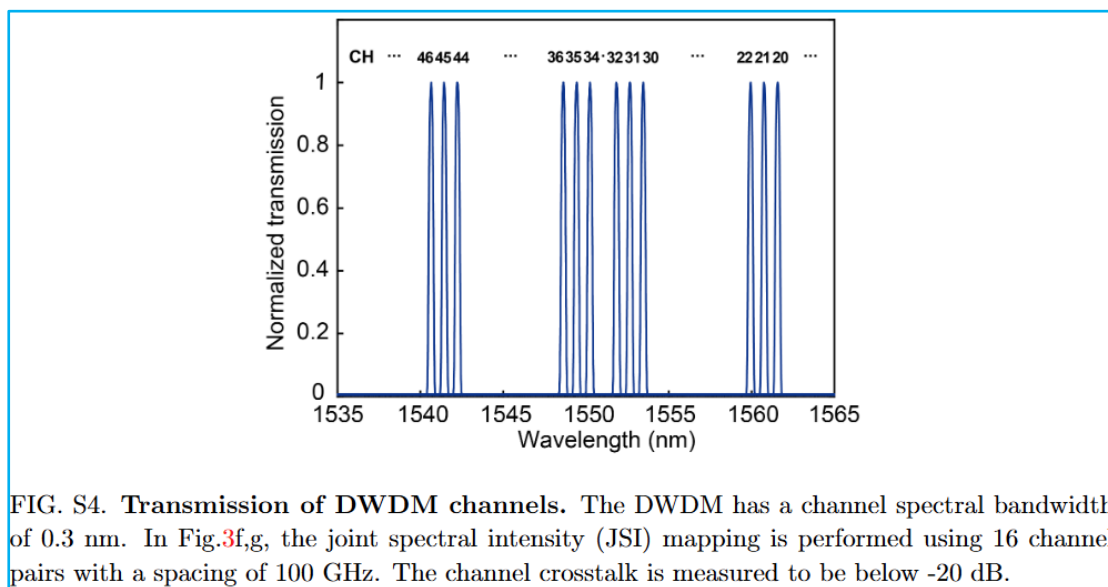


FIG. S2. Type-0 and type-I SPDC photon count balancing using integrated microheater. a, Applied electrical power with a periodic triangular waveform to the localized microheater on the type-0 PPLN nanophotonic waveguide. b, Type-0 (blue) and type-I (red) SPDC photon counts as a function of applied electrical power. While type-0 SPDC count rate is modulated, type-I count rate remains unaffected, indicating robust thermal control and negligible thermal crosstalk, respectively. Such localized thermal tuning enables balancing of type-0 and type-I photon count rates within the investigated bandwidth.

12. Specify any characterization graph measured to calibrate the DWDM used. How about the DWDM channel cross-talks? A suitable comment on the DWDM characterization is necessary. Mention the make of the DWDM and its transmission specifications.

The DWDM used in our setup has a channel bandwidth of ~0.3 nm, and the channel cross-talk is measured to be below -20 dB, seen in the following graph. In our experiment, the joint spectral intensity (JSI) mapping is performed using 16 channel pairs with a spacing of 100 GHz (~0.8 nm). Since the used channel spacing in the measurement is significantly larger than the filter bandwidth, this configuration ensures sufficient spectral isolation between neighboring channels and minimizes channel cross-talk. DWDM was bought from FS TECH PTE. LTD.

We have added the DWDM specifications in the revised manuscript.



the type-0 PPLN waveguide. The bandpass filter is then removed, and PBS outputs are routed through a DWDM module (FS TECH PTE. LTD., see transmission in Supplementary Information Fig.S4) to select channel pairs (CH21–CH45) for individual type-0 and type-I JSI measurements (Fig.3a(iii)). Coincidence countings (Fig.3b, c, f, g) are measured

13. What is a source meter? what is actually measured using it and how is it calibrated?

Thanks for raising this question. A source meter is a multi-function instrument that combines the capabilities of a power supply, digital multimeter (DMM), current source, and electronic load into a single unit. We realized that we made a mistake here. The instrument we used (Keithley 2230) is in fact a DC power supply with an internal current/voltage monitoring function. It is used to drive the integrated microheaters on the chip. The on-chip heater has much higher resistance than the leads, so we can assume most power are dissipated on the heater. The instrument has factory calibration certificate.

We have revised the description and added the equipment detail in the revised manuscript.

to-digital converter (TDC). We heat up the global temperature to 50°C by TEC, roughly matching the PM wavelengths of the two PPLN waveguides and aligning the type-I PM wavelength to CH33 (1550.92 nm), and adjust the type-0 phase matching independently by fine tuning the power supply (Keithley 2230) power applied to the local microheater on the type-0 PPLN waveguide. The bandpass filter is then removed, and PBS outputs are

14. What was the maximum and minimum pump powers experimented for the long distance measurements?

For the long-distance entanglement distribution measurements, the pump power was kept at -2 dBm.

We have added the details in the revised manuscript.

detection, to compensate for the accumulated dispersion of $\sim 650 \text{ ps nm}^{-1}$. The on-chip pump power is kept at -2 dBm during the measurement.

15. In pages 10, 11:

i) What is the PM wavelength that was precisely kept in the experiment, to obtain the results of Fig. 1(d)?

ii) what temperature is kept for these measurements in Figs. 2-b,c,e?

iii) specify what lasers are used and their tunability range.

iv) What are the details of this dispersion compensation module that is used? Specify any characterization graph measured to calibrate this.

i) In all the polarization-entanglement measurements (Fig. 1d, 3, 4), the pump wavelength is fixed at 775.46 nm, corresponding to DWDM channel CH33 at the fundamental wavelength.

ii) The measurements shown in Fig. 2b, Fig. 2c, and Fig. 2e were performed at room temperature, unless otherwise specified.

iii) A Santec TSL-570 tunable laser is used for the characterization measurements in Fig. 2. The laser itself has a tuning range from 1500 nm to 1630 nm. For the SPDC measurement, a Newport TLB-6712 Velocity laser is used, with a tuning range from 765 nm to 781 nm.

iv) The dispersion compensation module (DCM) consists of a spool of anomalous-dispersion fiber. We use a 40 km DCM, introducing about 650 ps/nm of anomalous dispersion into the system, to compensate the accumulated fiber dispersion and realigning the arrival times of different frequency components of the entangled photons, for entanglement distribution measurement between Charlie and David. The dispersion information is obtained from the manufacturer; we did not calibrate ourselves.

We have added these details in the revised manuscript.

entangled photon-pair preparation. A tunable CW laser (Newport TLB-6712 Velocity) at 775.46 nm, corresponding to ITU channel CH33 at its FH wavelength, is used as the pump. The pump laser has a linewidth of $<200 \text{ kHz}$, corresponding to a coherence length much longer than the spatial separation between the two PPLN sections, which make the photon pairs generated from the two quasi-phase-matched regions remain indistinguishable with respect to the pump coherence. The pump is coupled into optical fiber via a collimator, with

a width of $2 \text{ }\mu\text{m}$ with an etching depth of 300 nm . The poling periods for type-0 and type-I QPM process is calculated to be $4.76 \text{ }\mu\text{m}$ and $4.54 \text{ }\mu\text{m}$ at room temperature, according to $\Lambda = \frac{\lambda_{\text{FH}}}{2(n_{\text{SH}} - n_{\text{FH}})}$, where λ_{FH} is the FH wavelength (1550 nm) and $n_{\text{SH}/\text{FH}}$ is the corresponding effective index of the involved SH/FH modes. We evaluate the nonlinear

c. Experimental details for classical characterizations of D-QPM PPLN waveguide. We characterize the nonlinear performance of the device at room temperature. To extract the

and verified using an infrared polarimeter before coupling into the waveguide. For Fig.2a, the CW pump laser (Santec TSL-570) is fixed at the PM wavelength of type-0 and type-I SHG, while the pump power is swept and the SHG output is measured with an infrared power meter. Both pump and SHG powers are referenced on-chip. For Fig.2b, c, two

entangled photon-pair preparation. A tunable CW laser (Newport TLB-6712 Velocity) at 775.46 nm, corresponding to ITU channel CH33 at its FH wavelength, is used as the pump. The pump laser has a linewidth of <200 kHz, corresponding to a coherence length much longer than the spatial separation between the two PPLN sections, which make the photon pairs generated from the two quasi-phase-matched regions remain indistinguishable with respect to the pump coherence. The pump is coupled into optical fiber via a collimator, with

10.8 dB, respectively. For the longest-distance measurement between Charlie and David (50.8 km), a 40 km-long anomalous-dispersion fiber spool is added to the David path before detection, to compensate for the accumulated dispersion of $\sim 650 \text{ ps nm}^{-1}$. The on-chip

16. What were the total channel losses in the deployed fiber (in dB), and how were they distributed?

The round-trip losses for the deployed fiber links to the four users are measured to be 2.1 dB (Alice), 5.2 dB (Bob), 10.4 dB (Charlie), and 10.8 dB (David).

We have added the details in the revised manuscript.

Deployed metropolitan fiber loop lengths for Alice, Bob, Charlie, and David paths are 0.9 km, 3.4 km, 28.3 km, and 22.4 km with a round-trip loss of 2.1 dB, 5.2 dB, 10.4 dB, and 10.8 dB, respectively. For the longest-distance measurement between Charlie and David

17. PMD Compensation: The authors mention compensating for polarization mode dispersion (PMD) in the deployed fiber.

- How was the PMD characterized or quantified?
- What compensation technique was used?
- Was the compensation static or dynamically stabilized during operation?
- A sufficient study or characterization of the polarization drift and fluctuations in the deployed fiber is missing. Did the authors monitor the same during the course of the experiment? If not done, such a study is essential in this manuscript. It is suggested to detail the overall magnitude and timescale of polarization fluctuations observed in the deployed metro fiber. What specific stabilization or compensation technique was implemented to mitigate polarization drift during long-distance entanglement distribution?

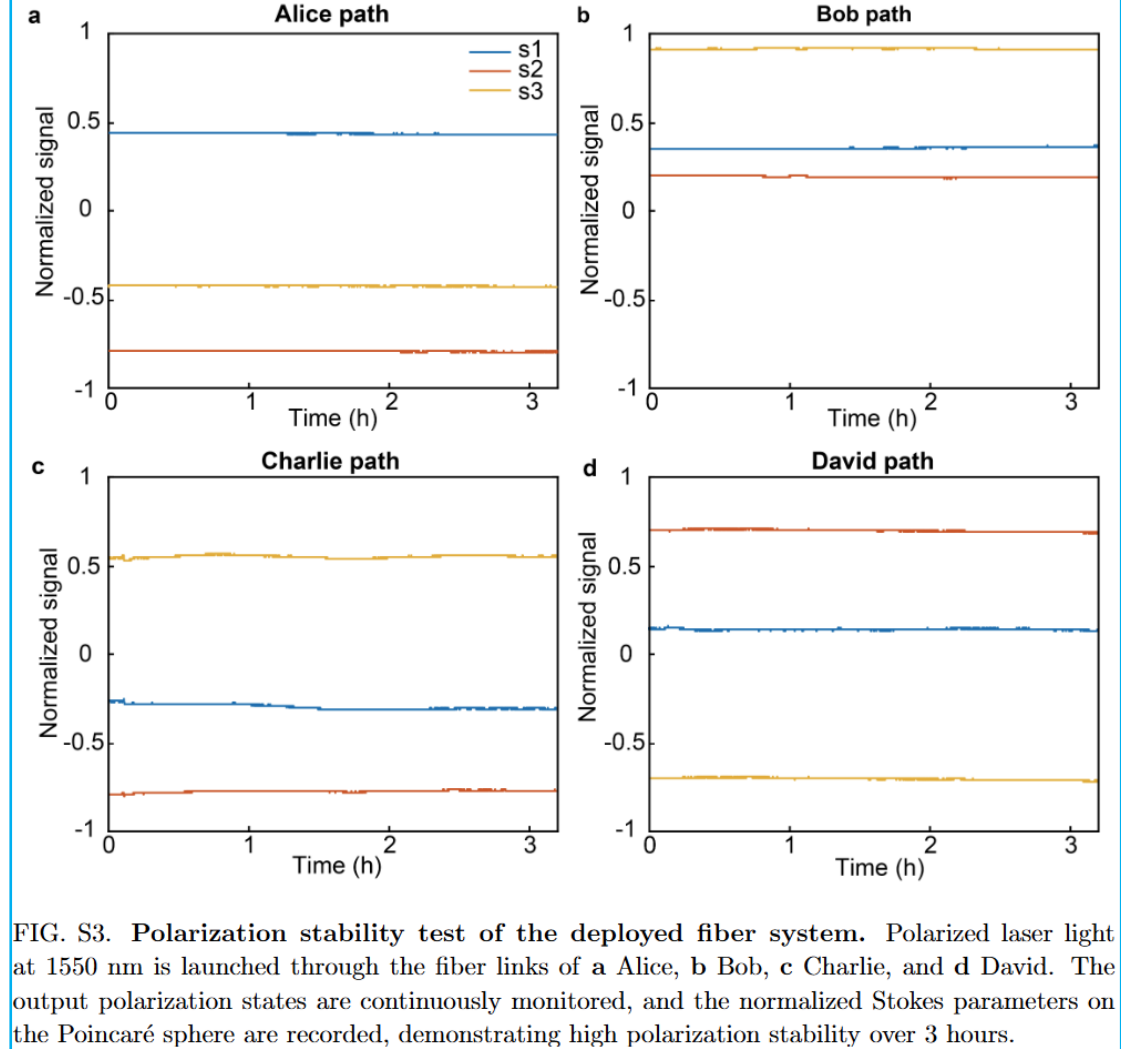
We thank the reviewer for these important comments regarding PMD and polarization stability in the deployed fiber network.

In the present experiment, PMD was not directly characterized or compensated. Our discussion in the manuscript was intended to acknowledge it as a potential limiting factor for long-distance entanglement distribution and to point to established mitigation strategies for future large-scale deployments. For clarity, PMD refers to the differential group delay (DGD) between the principal states of polarization in an optical fiber, arising from residual birefringence and its stochastic variations along the link. We did not perform dedicated measurements of the PMD coefficient or time-resolved DGD in this work. The polarization drift compensation will be considered in the future work, when the source is applied to practical applications [*Physical Review A* 112.3 (2025): 032620; *Applied Physics Letters* 117.12 (2020)].

Regarding polarization stability, the deployed metropolitan fiber links are found to be

relatively stable over the timescale of our measurements (see the plots below). Active polarization stabilization would nonetheless be beneficial for long-term autonomous operation in practical quantum networks.

We have clarified these points in the revised manuscript.



ties reported here represent conservative estimates of real-world performance. Although the deployed fiber links have been tested with high stability (see details in Supplementary Information Fig.S3), implementing active polarization stabilization or advanced compensation strategies would help to mitigate the PMD effect and maintain high-fidelity transmission over extended distances for long-term operation⁶². Alternatively, narrowing the photon-pair spectral bandwidth, for instance, by employing microring resonators that generate ultra-bright, narrow-band photon pairs, can further suppress the impacts of both PMD and chromatic dispersion⁵³. These approaches will collectively enhance the system robustness and scalability for practical quantum network deployment.

Minor points:

18. In page 5, first line below Fig. 2: it is rather “spectral brightness” instead of “brightness”.

19. Page 8, line 8 from the top: type – “Bod” should be replaced by “Bob”.

We thank the reviewer to point these out. We have corrected in the revised manuscript.