

<https://doi.org/10.1038/s41534-026-01290-3>

Integrated high-quality multi-wavelength quantum light source compatible with ITU Channel Grid



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Scalable quantum networks require high-quality multi-wavelength light sources to enable simultaneous quantum communication among multiple users¹. However, realizing such sources with high brightness, low noise, and chip-scale integration remains challenging. We demonstrate a high-quality and multi-wavelength quantum light source based on a periodically poled thin-film lithium niobate (TFLN) microring resonator employing spontaneous parametric down-conversion (SPDC) with a 100-GHz free spectral range (FSR), compatible with International Telecommunication Union (ITU) Channel Grid. In our experiment, twelve pairs of non-degenerate photon pairs are generated, exhibiting a photon-pair generation rate (PGR) of 817 MHz/mW, brightness of 1.86×10^9 Hz/mW²/GHz, and a coincidence-to-accidental ratio (CAR) of $51,829 \pm 2204$. The source enables predictable single photons with $g^{(2)}(0) = 0.015 \pm 0.006$ and energy-time entanglement with 99.5% raw visibility. Operating at room temperature, telecom wavelengths, and compatible with network channels, this work represents a crucial step toward realistic scalable, integrated quantum photonic networks in the future.

Quantum science and technology has transformed modern information science by introducing a fundamentally new framework for the generation, transmission, and processing of nonclassical states and information. Photons possess exceptional coherence and robustness against environmental perturbations, making them ideal carriers for quantum computation^{2–4} and widely employed in quantum communication^{5–7}. For large-scale quantum information processing, a fully integrated on-chip quantum system typically comprises key components such as quantum sources^{8–12}, quantum detectors^{13,14}, and quantum transducers¹⁵. Among them, quantum light sources are elementary building blocks for realizing quantum networks^{16–18}, which are essential for both fundamental insights and down-to-earth applications. Especially, multi-wavelength quantum light sources have proven to be an indispensable component to establish a fully and simultaneously connected multiple-user quantum networks¹⁹.

Entangled photon pairs are commonly generated through the second-order ($\chi^{(2)}$) and the third-order ($\chi^{(3)}$) nonlinear parametric processes, including SPDC and spontaneous four-wave mixing (SFWM)^{20–23}. Compared with devices based on $\chi^{(3)}$ nonlinearities, those exploiting $\chi^{(2)}$ nonlinear effects exhibit orders-of-magnitude stronger nonlinear responses and are free from unwanted $\chi^{(3)}$ -related processes. Among various $\chi^{(2)}$ materials,

thin-film lithium niobate (TFLN) stands out owing to its strong $\chi^{(2)}$ non-linearity, wide transparency window, and excellent capability for photonic integration²⁴. Recently, cavity-enhanced SPDC in TFLN microresonators has leveraged the advantages of high quality (Q) factors, small mode volumes, and flexible dispersion engineering, enabling efficient generation of multi-wavelength quantum light^{25,26}. Despite these remarkable advances, realizing high-quality multi-wavelength quantum light sources at wide telecom wavelengths compatible with network channels—particularly in terms of generation rate and entanglement performance—remains challenging. Further investigation into the generation and manipulation of entanglement from optical cavities is therefore essential for advancing scalable quantum photonic technologies.

Here, we demonstrate a high-quality, multi-wavelength quantum light source based on a periodically poled TFLN microring resonator chip operating via the SPDC process. By optimizing phase matching and precisely engineering the dispersion, the generated photon pairs, with a free spectral range (FSR) of 100 GHz, cover the entire range of commercial dense wavelength division multiplexing (DWDM) channels—corresponding to ITU channels CH20 to CH60 from 1529 nm to 1561 nm. The source exhibits a PGR of 817 MHz/mW, a brightness of 1.86×10^9 Hz/mW²/GHz,

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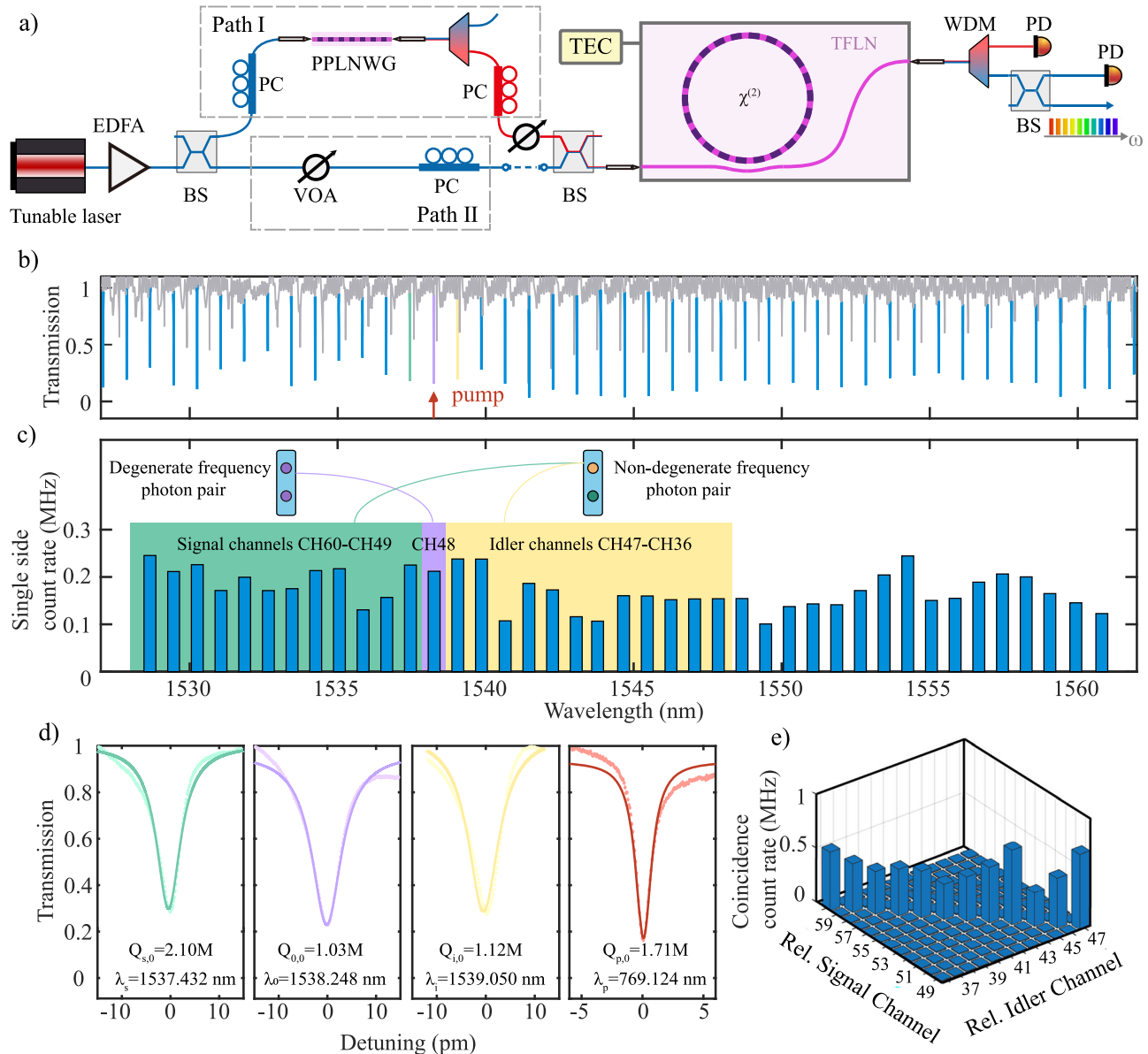


Fig. 1 | Characterization of multi-wavelength correlated photon pairs.

a Experimental setup for the generation of multi-wavelength correlated photon pairs. EDFA erbium-doped fiber amplifier, BS beam splitter, PC polarization controller, PPLNWG periodically poled lithium niobate waveguide, VOA variable optical attenuator, WDM wavelength-division multiplexer, TEC thermoelectric cooler, PD photodetector. **b** Transmissions from 1527 to 1563 nm with an FSR of

100 GHz. **c** Spectrum of single side count rate at different channels of a DWDM. The shaded areas are the spectrum range of correlated photons for the test. **d** Resonance spectra of telecom TE₀₀ modes and visible TM₀₀ mode. The modes from left to right are the signal mode, degenerate mode, idler mode, and pump mode, with corresponding central wavelengths of 1537.432 nm (CH49), 1538.248 nm (CH48), 1539.050 nm (CH47), and 769.124 nm, respectively. **e** Joint spectral intensity.

and a CAR of $51,829 \pm 2204$. Moreover, the source enables a predictable single-photon generation with a second-order correlation of $g^{(2)}(0) = 0.015 \pm 0.006$, and an energy-time entanglement visibility of 99.5%. In addition, we also demonstrate the generation of high-quality degenerate photon pairs. With its high brightness and wide spectral span, this photon-pair source offers a promising platform for integrated quantum information processing and multi-channel quantum networking in the future.

Results

Multi-wavelength correlated photon pairs

The experimental setup for the generation of multi-wavelength correlated photon pairs is shown in Fig. 1a. The tunable laser at the telecom band is divided into two paths by a 90%:10% beam splitter (BS), with one path (Path I) utilizing the PPLN waveguide for frequency doubling to generate visible light, which serves as the tunable visible light source during SPDC. The

isolation for the telecom band of WDM in Path I is 180 dB, which is used to suppress the infrared wave of PPLN second harmonic generation (SHG) process to less than single-photon level. When both Path I and Path II are connected, it allows for the verification of whether the dual-resonance condition in the cavity-enhanced second-order nonlinear process is strictly satisfied²⁷, ensuring that the SPDC process operates in its optimal state.

Figure 1b illustrates the transmission properties of the microring in the telecom band. The blue lines in the transmission spectrum indicate the TE₀₀ mode family, with an FSR of 0.80 nm (100 GHz), consistent with the theoretical prediction. We demonstrate that the signal, degenerate, idler, and pump modes with corresponding central wavelengths of 1537.432 nm (CH49), 1538.248 nm (CH48), 1539.050 nm (CH47), and 769.124 nm, respectively—indicated by the green, purple, yellow, and red lines, respectively—exhibit loaded Q factors (Q_L) of 298k, 258k, 258k, and 485k, and intrinsic Q factors (Q_0) of 2.10M, 1.03M, 1.12M, and 1.71M, as shown in Fig. 1d.

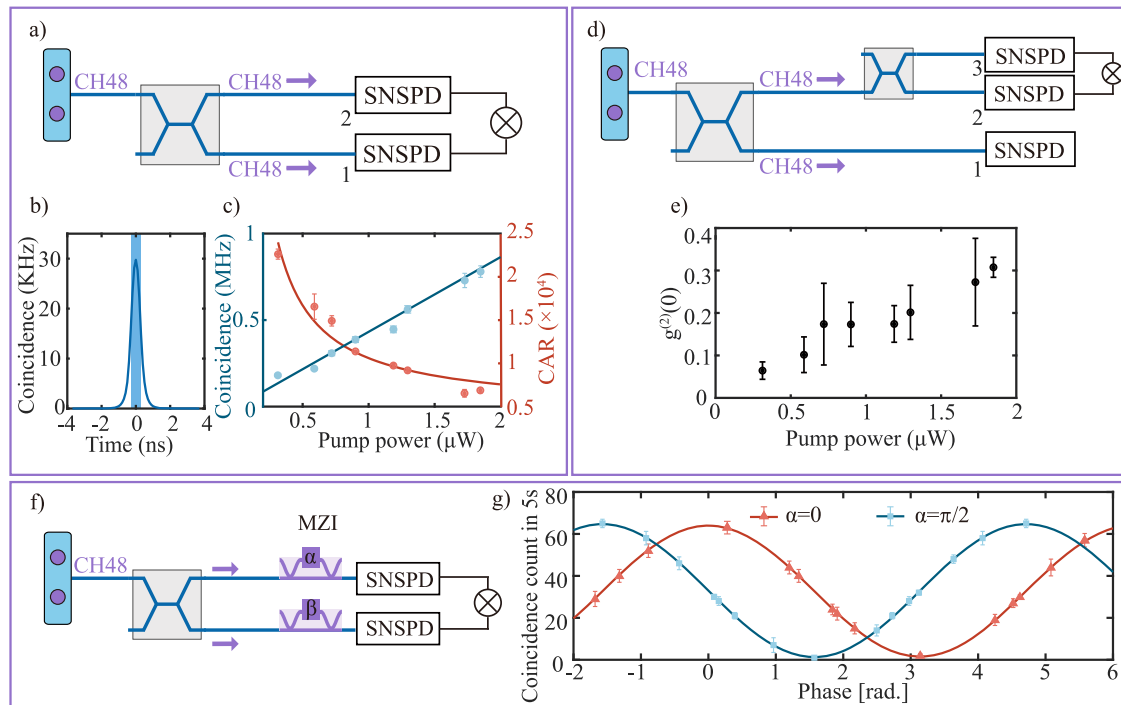


Fig. 2 | Characterization of degenerate photon pairs. Experimental setups for correlation properties **a**, measurement of the predictable second-order correlation **d** and energy-time entanglement **f**. **b** correlations for degenerate photon-pair. **c** Coincidence counts rate and coincidence-to-accidental ratio versus pump power.

Figure 1c shows the single side photon count rates through a DWDM with 100-GHz resolution at 1 μ W pump power. The generated photon pairs cover the entire range of DWDM channels—from 1529 nm to 1561 nm, corresponding to ITU channels CH20 to CH60. CH48 corresponds to the generated photon pairs of degenerate frequency, others are the generated photon pairs of non-degenerate frequency. The variation in the detected photon rates for different resonance wavelengths can be explained by the difference in the Q factors and coupling efficiency of the infrared resonator modes. According to theoretical calculations²⁸, the bandwidth for nondegenerate SPDC is as large as 76 nm. Coincidences among twelve non-degenerate pairs in a range of green and yellow shaded areas in Fig. 1c are measured using paired DWDMs, and results are shown in Fig. 1e, which indicates that coincidences are obtained only with wavelength correlated ones. Since photon pairs are generated simultaneously, corresponding signal photons also exist in the wavelength range below 1529 nm. However, due to the measurement bandwidth limitation of the DWDM module, only twelve pairs of photon pairs are experimentally recorded. These results indicate that, in principle, at least twenty-eight pairs of photon pairs are generated simultaneously during the SPDC process.

Degenerate-frequency predictable single-photon source

Experimentally, the resonance corresponding to CH48 is selected to characterize the quality of the degenerate photon pairs. As shown in Fig. 2a, the photon pairs in CH48 are divided into two paths by a 50:50 BS and directed to superconducting nanowire single-photon detectors (SNSPDs). The SNSPDs exhibit a dark count rate of 20–100 Hz and a detection efficiency over 87%. They are connected to a time-tagging unit for photon counting and coincidence analysis. The generation of photon pairs is confirmed by the two-photon correlation histogram shown in Fig. 2b, which depicts the distribution of arrival-time differences between the two photons. The full width at half maximum (FWHM) of the coincidence peak is measured to be 532 ps, and a coincidence window of 50 ns is therefore chosen to include all correlated events.

Red and blue solid lines indicate the fitted curves. **e** $g^{(2)}(0)$ as the function of the pump power. **g** Results of Franson interference for $\alpha = 0$ and $\alpha = \pi/2$ with unbalanced Mach-Zehnder interferometers (MZIs).

The PGR and CAR and the results are shown in Fig. 2c. Typically, the PGR is calculated as $PGR = (N_1 N_2) / N_{12}$, where N_1 , N_2 and N_{12} are the counts for single detector and two-photon coincidence counts, respectively. The efficiency of SPDC is estimated to be 430 MHz/mW. Theoretically, the PGR of the degenerate photon pairs is 591.7 MHz/mW (see Note S4), estimated based on the normalized SHG efficiency of 112,260%/W obtained from the TFLN microring resonator (see Fig. S3 in Note S3). The generated photons' linewidth²⁹ is estimated as $\delta\nu = 0.64 \times \kappa_{0,i} / 2\pi = 483.8$ MHz, where $\kappa_{0,i} / 2\pi$ is total coupling rate of degenerate mode. The brightness is thus calculated as 0.89×10^9 Hz/mW²/GHz. This normalization accounts for the quadratic scaling of SPDC with pump power and the measured linewidth of the resonances. In practice, the raise of intracavity power renders dramatical resonant mode detuning especially at visible band due to the thermal and photorefractive effect^{30–32}, resulting in a limitation on PGR. The CAR reaches up to $24,749 \pm 1648$ at a low pump power of 312 nW and decreases as the pump power increases, which mainly attributes to the increase in multi-pair generation.

The single-photon purity is evaluated by measuring the predictable second-order correlation function $g^{(2)}(0)$ using a Hanbury Brown and Twiss (HBT) setup^{33,34}. As illustrated in Fig. 2d, one arm of the photon pairs from CH48—originally divided into two paths—is further split equally into two branches, labeled as Path 2 and Path 3. Together with the other arm (Path 1), the correlation function is calculated as $g^{(2)}(0) = (N_{123} N_1) / (N_{12} N_{13})$, where N_1 is the single count rate, and N_{12} , N_{13} , and N_{123} denote the coincidence count rates. The measured values of $g^{(2)}(0)$ at different pump powers are presented in Fig. 2f. A value of $g^{(2)}(0) = 0.064 \pm 0.020$ is obtained at an idler photon count rate of 199 kHz, which is below the classical correlation limit, confirming the quantum nature of the predictable single-photon source. Owing to multi-pair generation in the SPDC process, $g^{(2)}(0)$ increases with increasing pump power. The error may be attributed to minor fluctuations and instability of the microcavity during the measurement process.

The generated degenerate photon pairs are expected to exhibit energy-time entanglement, which can be verified through a Franson-type two-

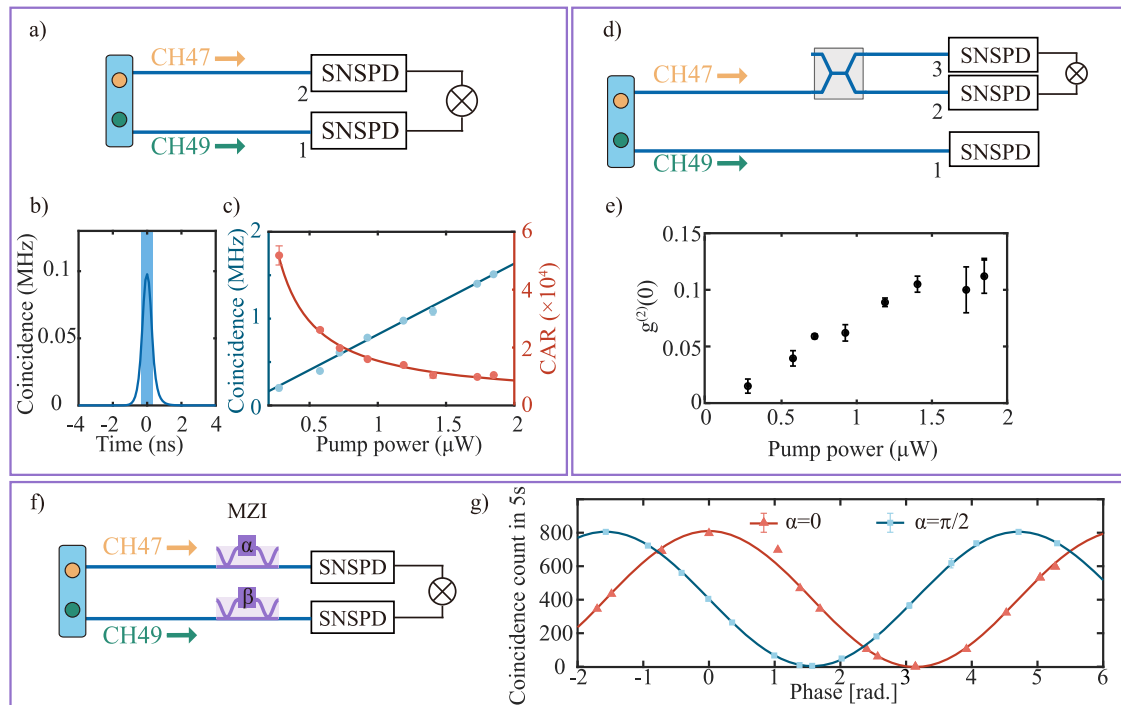


Fig. 3 | Characterization of non-degenerate photon-pair. Experimental setups for correlation properties **a**, measurement of the predictable second-order correlation **d** and energy-time entanglement **f**. **b** correlations for CH47 and CH49. **c** Coincidence counts rate and coincidence-to-accidental ratio versus pump power.

Red and blue solid lines indicate the fitted curves. **e** $g^{(2)}(0)$ as a function of the pump power. **g** Results of Franson interference for $\alpha = 0$ and $\alpha = \pi/2$ with unbalanced Mach-Zehnder interferometers (MZIs).

Table 1 | Comparison of integrated photon-pair sources on different platforms

Platform	Structure	PGR@1 mW (Hz)	Brightness@1mW (Hz/mW ² /GHz)	Number of photon pairs	Visibility	Ref.
SiN ^a	Microring	3.04×10^7	1.2×10^9	1	97.3%	48
SiN ^a	Microring	1.15×10^6	9.6×10^6	8	99.4%	49
SiN ^a	Microring	2.3×10^6	1.1×10^7	1	82.7%	20
Si ^a	Microring	1.5×10^6	1.6×10^8	1	95.9%	50
SiC ^b	Microring	9.6×10^5	1.9×10^5	1	86.0%	51
AlN ^b	Microring	5.8×10^6	8.3×10^6	1	–	28
TFLN ^b	Waveguide	7.78×10^8	3.4×10^5	–	98.8%	52
TFLN ^b	Waveguide	2.3×10^8	4.6×10^6	–	96.8%	53
TFLN ^b	Microring	2.7×10^9	2.3×10^9	5	–	25
TFLN ^b	Microring	8.17×10^8	1.86×10^9	12	99.5%	This work

^aScheme based on SFWM.

^bScheme based on SPDC.

photon interference, demonstrating a violation of Bell's inequality^{35,36}. Figure 2f depicts the experimental setup for measuring the energy-time entanglement. The degenerate photon pairs are first divided by a BS and then sent into two identical unbalanced Mach-Zehnder interferometers (MZIs) with controllable phase differences of α and β . The fixed arm path-length difference of each unbalanced MZI corresponds to a time delay of 1 ns. As shown in Fig. 2g, the energy-time entanglement is confirmed by the sinusoidal variation of coincidence counts as a function of the phase. The measured visibilities are $V = 93.8\%$ (red triangles) and $V = 96.9\%$ (blue squares) after background subtraction, corresponding to phase settings of $\alpha = 0$ and $\alpha = \pi/2$, respectively. According to the Clauser-Horne criterion, photon-pair entanglement requires a two-photon interference visibility of $V \geq 70.7\%$ (even without testing local realism)³⁷. The obtained visibilities significantly exceed this threshold, confirming strong energy-time entanglement of the generated photon pairs.

Non-degenerate-frequency predictable single-photon source

Similarly, the resonances at CH47 and CH49 are selected to characterize the quality of the non-degenerate photon pairs, as illustrated in Fig. 3a. The two-photon coincidence histogram, shown in Fig. 3b, exhibits an FWHM of 642 ps, corresponding to the cavity lifetime of the microring resonator. The PGR of the non-degenerate photon pairs is determined to be 817 MHz/mW, with a brightness of 1.86×10^9 Hz/mW²/GHz and a linewidth of 438.8 MHz, showing superior performance compared with similar integrated sources^{38–40}. Meanwhile, the CAR, which quantifies the signal-to-noise performance of the photon pairs, is measured to be $51,829 \pm 2204$ under a pump power of 312 nW and a coincidence count rate of 254 kHz.

As illustrated in Fig. 3d, we also measured the predictable second-order correlation function under a HBT experiment. The measured $g^{(2)}(0)$ value is 0.015 ± 0.006 at a signal photon count rate of 245 kHz, indicating excellent single-photon purity with negligible multi-photon probability. The energy-

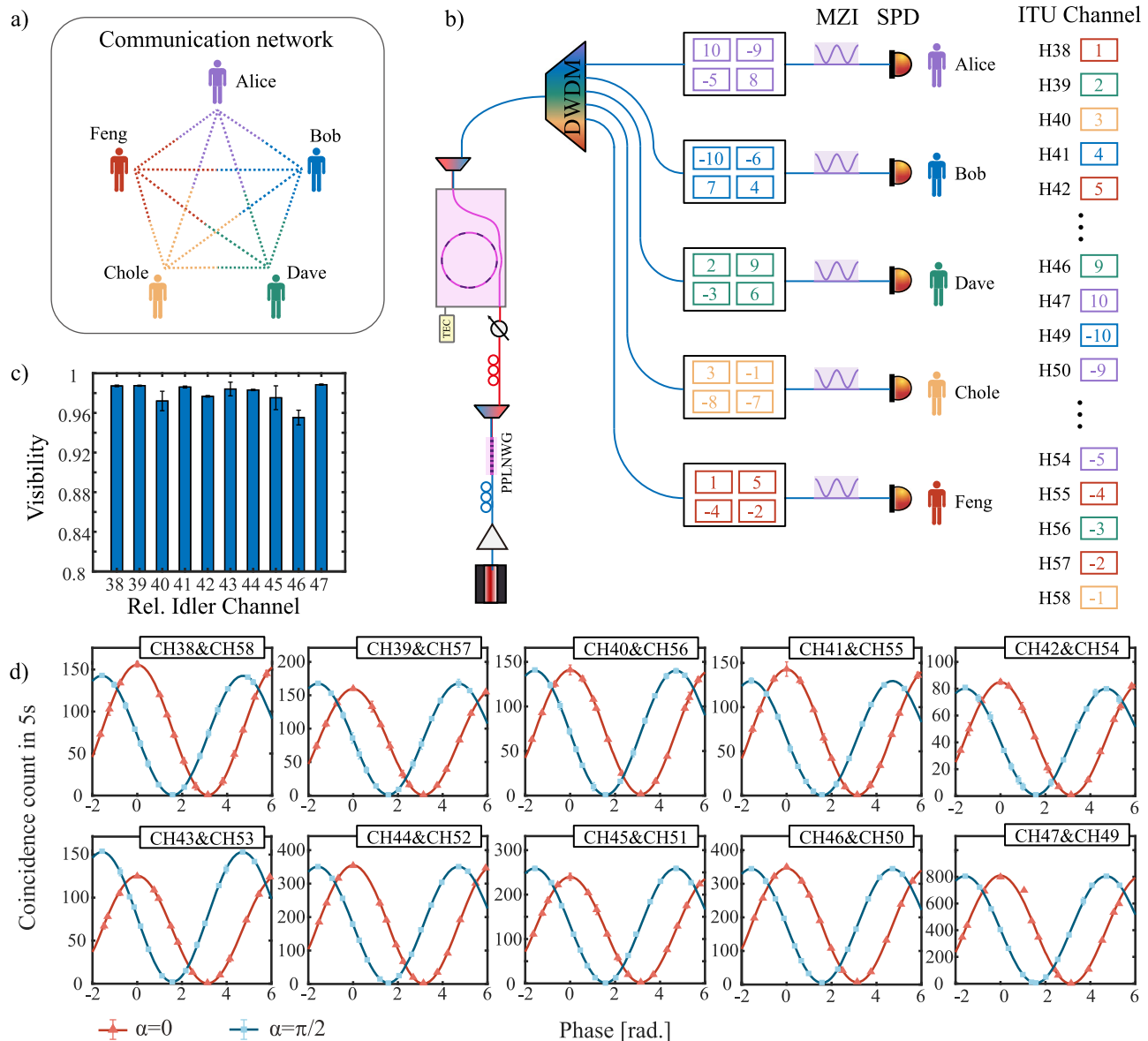


Fig. 4 | Characterization of fully connected quantum network. **a** Five-user fully connected quantum network. Dotted lines present correlated energy-time photon pairs between the users. **b** Physical structure of the quantum network. CH38 to CH47 are numbered from 1 to 10, respectively, and the numbers with opposite sign corresponding to CH58–CH49, respectively. The architecture of wavelength

allocation is omitted in the small rectangle multiplex blocks. Each small block with colored digital symbols constructs a wavelength group distributed by the network processor. **c** Measured interference visibility of each photon-pair channel. **d** Results of ten-pairs of photon pairs Franson interference for $\alpha = 0$ and $\alpha = \pi/2$ with unbalanced MZIs.

time entanglement measurement of photon pairs in CH47 and CH49 is shown in Fig. 3f. Similarly, two identical MZIs are used to control the phase differences α and β in the two paths. The sinusoidal dependence of coincidence counts on the phase difference demonstrates clear two-photon interference, with a fitted visibility of 99.5% (red triangles) and 98.8% (blue squares) corresponding to phase settings of $\alpha = 0$ and $\alpha = \pi/2$, respectively. The energy-time entanglement of non-degenerate photon pairs in other channels is analyzed in detail in the following section.

A detailed comparison of integrated photon-pair sources, employing various material platforms, device structures, and generation mechanisms, is provided in Table 1. Notably, our photon-pair source demonstrates near-optimal performance, achieving the highest photon-pair count among all platforms assessed. This is primarily attributed to the use of dispersion engineering and a second-order nonlinear process, which is inherently orders of magnitude larger than the third-order nonlinearity. Therefore, it offers significant advantages in PGR and photon-pair brightness over third-

order nonlinear processes. In third-order nonlinear processes, the small frequency difference among the pump, signal, and idler photons also necessitates large channel spacings to fully separate the generated modes, limiting the photon-pair count. Additionally, in the SFWM process, the pump frequency overlaps with that of the degenerate photon pairs, preventing their effective separation. However, degenerate photon pairs are of particular importance in applications such as quantum state engineering⁴¹ and quantum metrology⁴². In contrast, our approach benefits from a large frequency difference between the pump, signal, and idler photons, enabling efficient extraction of degenerate photon pairs and obviating the need for large channel spacings for pump separation.

Furthermore, the TFLN microring takes full advantage of the large second-order nonlinear coefficient of LN, while the high-quality factor of the microcavity significantly enhances light-matter interaction, resulting in a substantial improvement in the efficiency of the SPDC process. Although the SPDC process generally requires simultaneous resonance between the

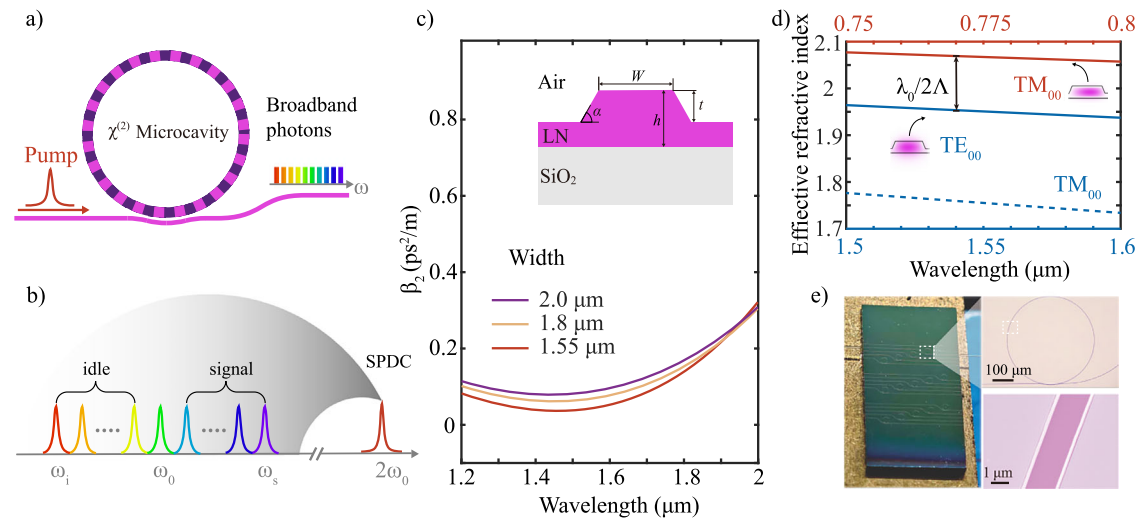


Fig. 5 | Design and characterization of periodically poled TFLN microring for SPDC. **a** Diagram of periodically poled TFLN microring for SPDC. **b** Schematic of broadband (degenerate) photon pairs generation via SPDC. **c** Simulated group velocity dispersion of TE₀₀ mode versus waveguide width. Inset: cross section of

TFLN nanowaveguide. **d** Simulated effective refractive indices (n_{eff}) versus wavelength. Inset: calculated mode profiles. **e** Photograph of the periodically poled TFLN microring chip. Optical and false-color SEM images of the microring (before poling).

pump, signal, and idler photons, which is challenging to achieve, we address this issue by using a synchronized scanning technique that allows us to directly observe the detuning of the optical frequencies and effectively overcome the resonance condition.

To the best of our knowledge, the experimental setup presented here is unique in achieving both ultra-high brightness and a high photon-pair count. Moreover, the system's performance can be further optimized toward the theoretical limit through enhanced spectral filtering techniques.

Fully connected quantum network

In the field of quantum information, communication nodes utilize shared high-fidelity entangled photon pairs to transmit information, which necessitates high-quality quantum light sources^{43–45}. As shown in Fig. 4a, we apply multi-wavelength photon pairs generated by the SPDC effect in this periodically poled TFLN microring to construct a fully connected quantum network, successfully establishing a 5-user fully connected quantum communication network based on the energy-time entanglement. It is important to note that only a portion of the generated photon pairs are selected here; in practice, a larger number of photon pairs can be used to extend the network and serve more users. The DWDM splits ten pairs ($C_5^2 = 10$) of ITU channels and distributed them to five end users. Each user established energy-time entanglement by adjusting the photons assigned to their four ITU channels via an MZL. The specific experimental setup and channel distribution scheme are illustrated in Fig. 4b. The interference contrast of entangled photon pairs serves as a key metric for evaluating the performance of quantum networks. To this end, the energy-time entanglement interference curves between users in this network are experimentally measured and shown in Fig. 4d. The red and blue curves represent the two-photon coincidence counts within 5 seconds after fixing the phase of one channel ($\alpha = 0$ and $\alpha = \pi/2$) and varying the phase β of the other channel. The interference contrast results between channel pairs are shown in Fig. 4c. These results demonstrate that the interference contrast between all users exceeds 95%, which proves that high-fidelity energy-time entangled photon pairs can be shared among users within our fully connected quantum network.

Our photon-pair source, based on cavity-enhanced SPDC, produces photon pairs with a broad bandwidth and narrow linewidth, allowing for the simultaneous generation of multiple pairs with high brightness. Experimental verification shows excellent energy-time interference contrast, suggesting its enormous potential for fully connected multi-user quantum communication networks.

Discussion

We have demonstrated high-quality multi-wavelength quantum light sources on the TFLN platform that are compatible with ITU channels and demonstrated its application in multi-user quantum networks. By careful dispersion engineering and employing type-I QPM SPDC in the periodically poled TFLN microring resonator, twelve pairs of photon pairs are obtained within a wavelength span over of 19 nm. At least twenty-eight entangled photon-pair channels are expected in principle. The PGR is estimated to be 817 MHz/mW, with a brightness of 1.86×10^9 Hz/mW²/GHz, a CAR of $51,829 \pm 2204$, a predictable second-order correlation $g^{(2)}(0) = 0.015 \pm 0.006$, and a raw energy-time entanglement visibility of $V = 99.5\%$. These results indicate that our high-quality, multi-wavelength quantum light source constitutes a promising platform for realistic quantum optical networks.

Methods

Device design and characterization

The schematic of the periodically poled TFLN microring designed for SPDC is depicted in Fig. 5a. Upon injecting a single-wavelength pump into the cavity, a comb-like spectrum of down-converted photon pairs is efficiently generated. Fig. 5b shows the schematic of broadband non-degenerate and degenerate correlated photon pairs generation via the SPDC process. The mechanism of correlated photon-pair generation is described in Note S1. In the non-degenerate (degenerate) case, a visible pump mode interacts with two (one) infrared modes, referred to as the signal and idler. The energy conservation condition is given by $\omega_p = 2\omega_0 = \omega_s + \omega_i$, while phase-matching (momentum conservation) requires $m_p = 2m_0 = m_s + m_i$, where ω and m denote optical frequencies and azimuthal mode numbers of the cavity modes, respectively. The subscripts p , s , i present pump, signal, and idler, respectively, and the subscript 0 refers to the degenerate case. For degenerate down-conversion, $\omega_s = \omega_i = \omega_0$ and $m_s = m_i = m_0$.

The bandwidth of the SPDC process relies critically on the phase-matching condition among the interacting modes which is dominated by the group velocity dispersion (GVD). The microring geometry is optimized for dispersion engineering to obtain a broad phase-matching bandwidth, as shown in Fig. 5c. Although a smaller microring width brings the GVD closer to zero at 1550 nm, it also reduces Q factor^{46,47}, which significantly affects the efficiency of SPDC. Considering these factors, the thickness h of the z-cut TFLN is 520 nm, and the side-wall angle α of the ridge waveguide is 60°. The top width W and the etching depth t are 1.55 μm and 320 nm, respectively. The second-order GVD parameter β_2 is calculated to be 3.81×10^{-2} ps² m⁻¹.

In addition, we also design a single pulley waveguide to access efficient dual-band coupling. The optimal width of the coupling waveguide and the coupling gap is determined to be 850 and 500 nm, respectively. The length of the pulley coupler is determined to be 67 μm to attain critical coupling for TM_{00} modes in the visible range, which is desired to maximize pump power inside microring cavity and hence the photon pair generation efficiency (see Fig. S1 in Note S2).

As shown in Fig. 5d, the TE_{00} mode in the infrared region shows weaker dispersion than the TM_{00} mode. Hence, a type-I SPDC process is employed to realize multi-wavelength photon-pair generation. The first-order quasi-phase matching (QPM) condition for the type-I (e-oo) SPDC process is achieved by periodic poling along the radial direction of the TFLN microring. The calculated QPM period is $\Lambda = 6.66 \mu\text{m}$. The detailed fabrication and poling process flow are found in Fig. S2 in Note S2. Fig. 5e shows a photograph of the TFLN microring chip sample. An optical image of the fabricated TFLN microring resonator is shown in Fig. 5e, with zoomed-in scanning electron microscope (SEM) image of the waveguide. The smooth surface and sidewalls of the waveguide demonstrate the high quality of our fabrication process.

Data availability

The data that support the findings of this study are available within the article.

Received: 27 January 2026; Accepted: 29 May 2026;

Published online: 06 June 2026

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Acknowledgements

This work was supported by the National Key Research and Development Program of China (2022YFA1205100, 2023YFA1407200); National Natural Science Foundation of China (12192252); Science and Technology Commission of Shanghai Municipality (24JD1401700); Shanghai Municipal Science and Technology Major Project (2019SHZDZX01-ZX06); Guangdong Provincial Quantum Science Strategic Initiative (GDZX2403003); Shuguang Program of Shanghai Education Development

Foundation and Shanghai Municipal Education Commission (24SG53); Yangyang Development Fund.

Author contributions

Yuanlin Zheng led the project since its conception and supervised all experiments. Jing Qiu and Yilin Yang performed the experiment and data analysis. Chennan Wu, Jiaqi Zhao, and Yuankai Liu contributed to the experiments. Hao Li developed the fabrication of microring resonator. Yuanhua Li, Yuanlin Zheng and Xianfeng Chen provided revisions. All authors participated in discussions of the results. Jing Qiu prepared the manuscript with assistance from all other co-authors. All authors have read and approved the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41534-026-01290-3>.

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