

Supplementary Information – Integrated polarization-entangled photon source for wavelength-multiplexed quantum networks

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SUPPLEMENTARY NOTE 1 – 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) 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 tunable telecom CW lasers are synchronously swept around the PM wavelengths, combined, and coupled into the waveguide to record the generated SFG power with a data acquisition system. For Fig.2d, SHG spectra at different temperatures are obtained by synchronously sweeping a telecom CW laser and monitoring the SHG power with a data acquisition system, while the chip stage temperature is stabilized using a TEC module. For Fig.2e, DC bias is applied to the integrated microheaters via electrical probes using a power supply, and the corresponding PM wavelength shifts are recorded.

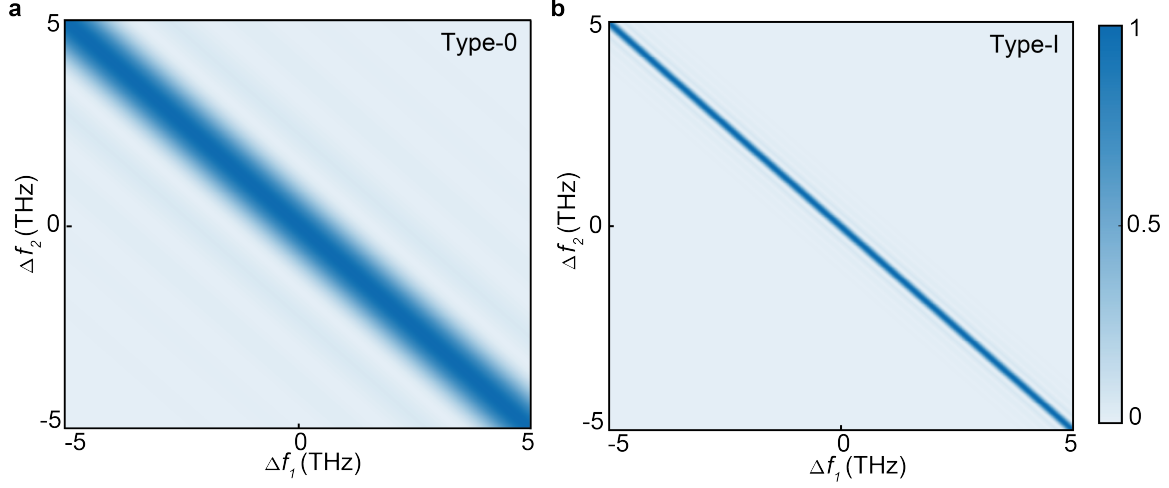
SUPPLEMENTARY NOTE 2 – EXPERIMENTAL DETAILS FOR NON-CLASSICAL CHARACTERIZATIONS OF D-QPM PPLN WAVEGUIDE

We use the experimental setups shown in Fig.3a to characterize the individual type-0 and type-I SPDC processes in the device. Figure 3a(i) illustrates the setup for polarization-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 PPLN regions remain indistinguishable with respect to the pump coherence. The pump is coupled into an optical fiber via a collimator, with its power controlled by a tunable attenuator and monitored by a power meter through a 10/90 beam splitter. Pump noise is suppressed using a short-pass filter, and the polarization is adjusted to TE with a PC before launching into the waveguide. After type-0 and type-I SPDC in the PPLN sections, the pump and photon pairs are collected with a lensed fiber and separated by a 775/1550 nm WDM. The residual pump is monitored by a power meter, while the photon pairs are passed through a long-pass filter to suppress pump leakage and Raman noise. TE and TM photons are then separated using a PC and polarization beam splitter (PBS) (Fig.3a(ii)). Polarization alignment is verified using SHG from calibrated pump 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

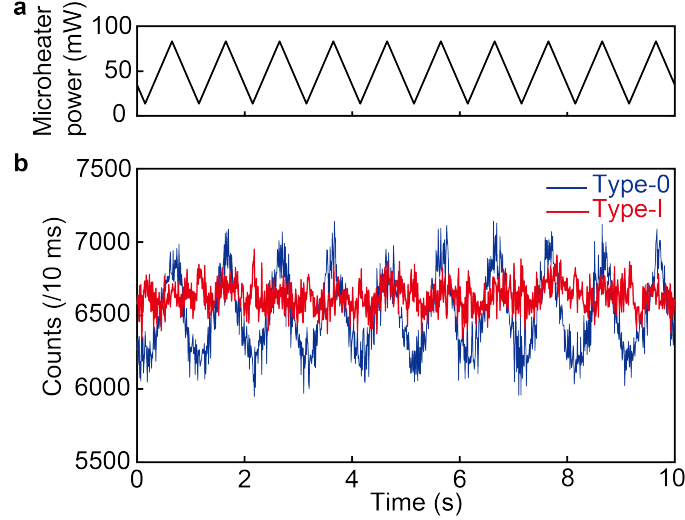
the brightness, a 15 nm bandpass filter centered at 1550 nm is initially inserted, ensuring equivalent collection of broad bandwidths. Each PBS output is further divided by a 50/50 beam splitter and detected by SNSPDs (IDQ ID281), with coincidences recorded on a time-to-digital converter (TDC). We heat 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 Figure 6) to select channel pairs from CH17 to CH49 for individual type-0 and type-I JSI measurements (Fig.3a(iii), Fig.3f, g). Coincidence countings (Fig.3b, c) from a selected channel pair (CH21-CH45) are also measured 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 correlation ($g_H^{(2)}$) measurements (Fig.3d, e), CH45 is split by a 50/50 beam splitter, and both outputs are detected by SNSPDs together with heralded CH21 photons (Fig.3a(iv)). A virtual delay (τ) is introduced in one of the split arms using the time tagger to extract $g_H^{(2)}(\tau)$.

SUPPLEMENTARY NOTE 3 – EXPERIMENTAL DETAILS FOR POLARIZATION ENTANGLEMENT MEASUREMENTS.

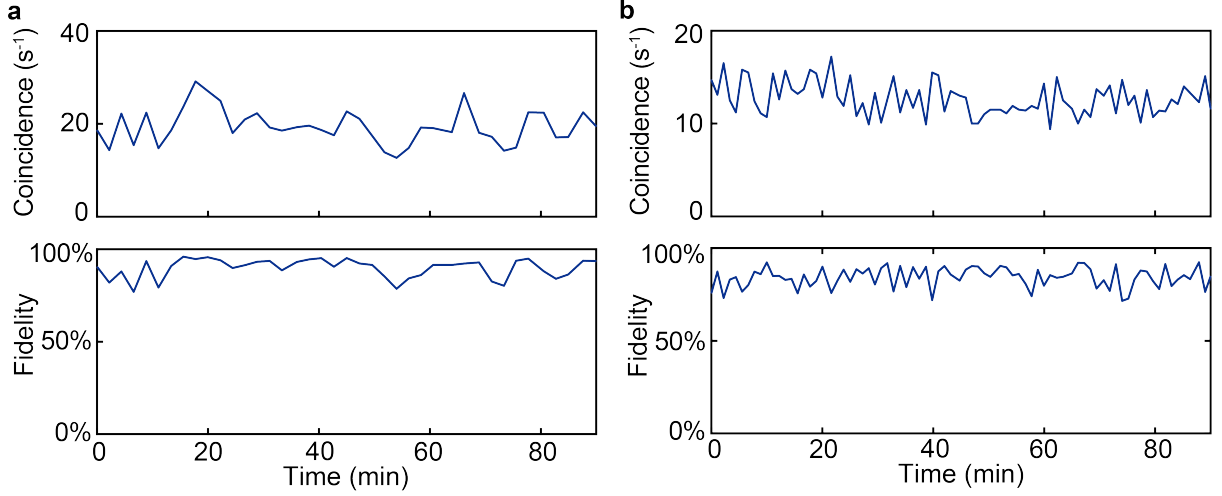
To characterize polarization entanglement, the source output (Fig.3a(i)) is connected to the detection setup (Fig.4c). The generated photon pairs are separated by a DWDM module, and photons from the selected channel pairs are directed into two free-space arms. Each arm passes through a sequence of QWP–HWP–QWP to compensate for fiber birefringence, followed by a HWP and PBS for polarization state projection. The wave plates are mounted on motorized rotation stages under programmable electrical control, enabling automated polarization scanning. The second HWP in the upper arm is fixed at an angle corresponding to one of H, V, D, and A bases, while the HWP in the bottom arm is rotated over 90°, which projects the entangled photons into the specific polarization base. The projected photons are then coupled back into fibers and detected by SNSPDs for coincidence counting. Polarization entanglement measurements are conducted for selected channel pairs CH31-CH35 and CH21-CH45 (Fig.1d). These are chosen to show that both nearly degenerate and far non-degenerate photon pairs work for this wavelength-multiplexed source. Other channel pairs could also work as well. For long-distance multi-user entanglement measurement (Fig.4e), after wavelength demultiplexing, two selected channel pairs (CH31-CH35, CH21-CH45) are distributed into four deployed optical fiber links, named Alice, Bob, Charlie, 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. 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. The on-chip pump power is kept at 0.63 mW during the measurement. 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 ~ 650 ps nm⁻¹.



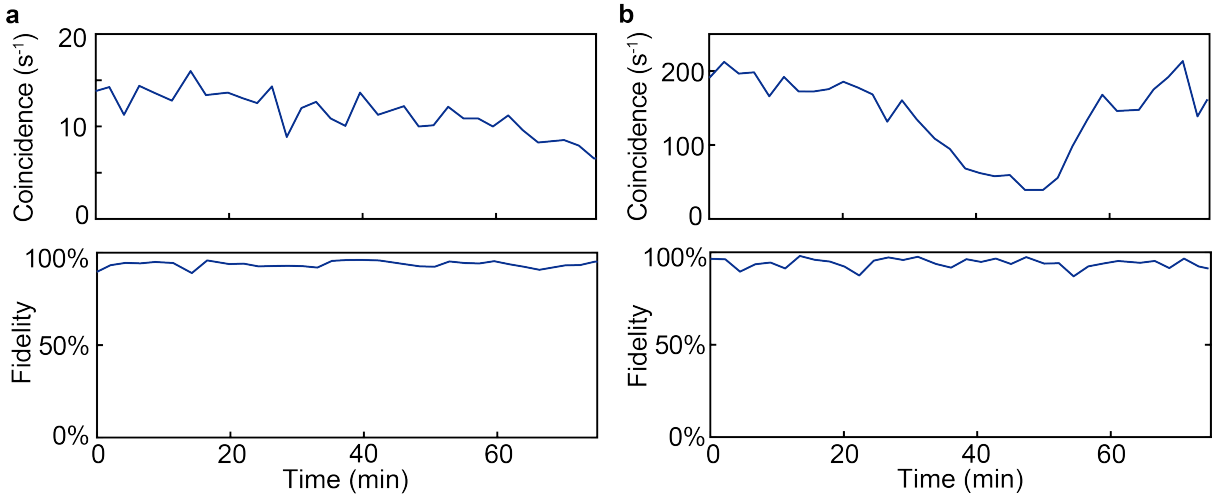
Supplementary Figure 1. **Simulated phase-matching function** for **a**, type-0 and **b**, type-I PPLN nanophotonic waveguides used in the experiment.



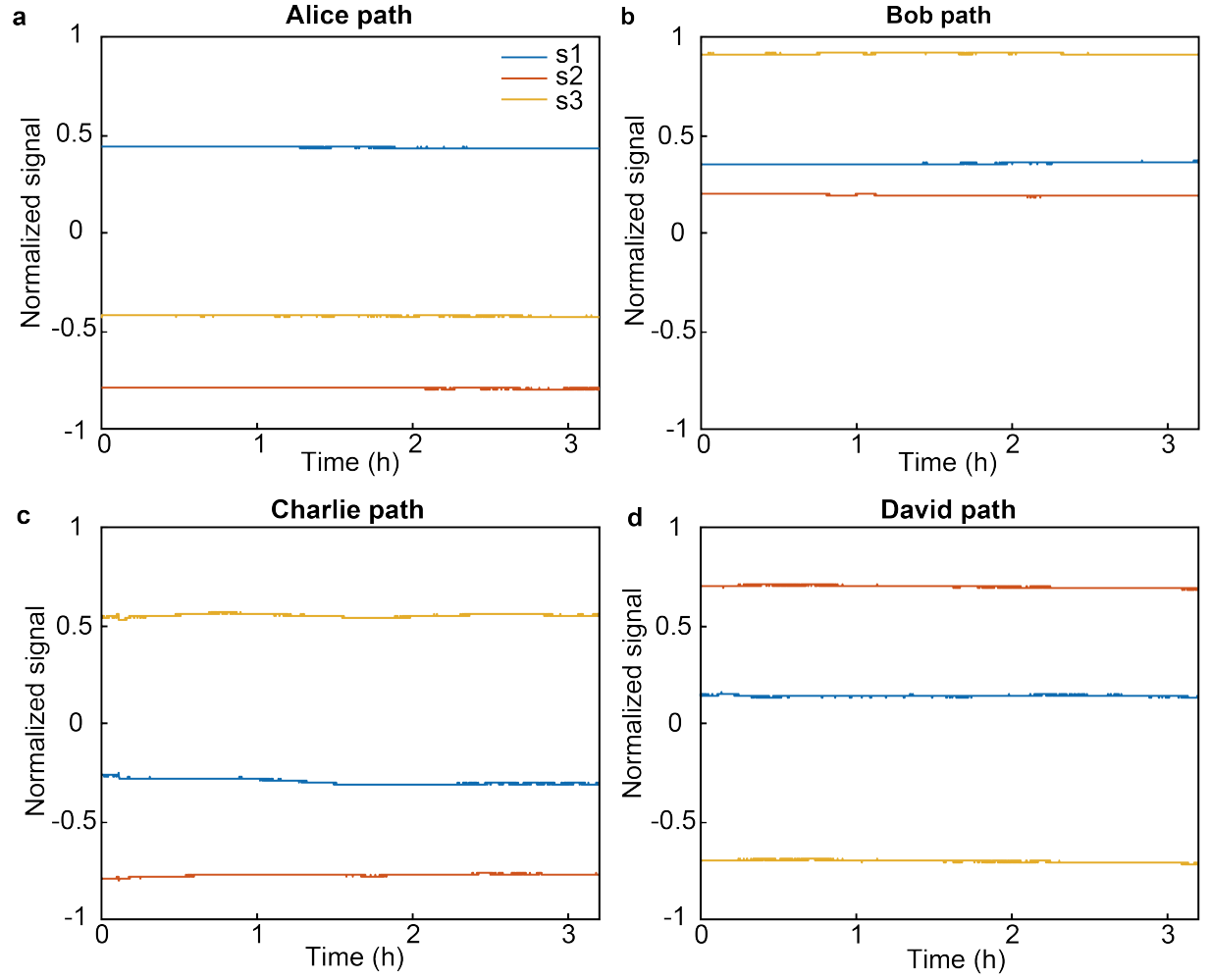
Supplementary Figure 2. **Type-0 and type-I SPDC photon count balancing using integrated microheater.** **a**, Applied electrical power with a periodic triangular waveform to the localized microheater on the type-0 PPLN nanophotonic waveguide. **b**, Type-0 (blue) and type-I (red) SPDC photon counts 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.



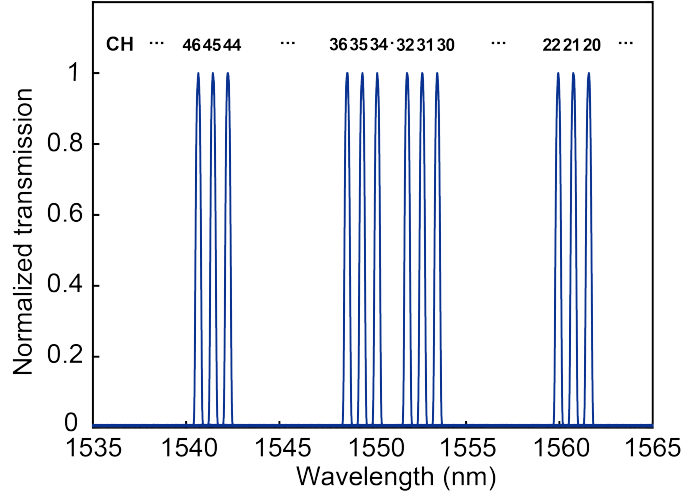
Supplementary Figure 3. **Representative stable operation of polarization-entangled photon-pair generation in the deployed fiber network.** One representative user-pair configuration (**a** Alice - David and **b** Bob - Charlie) from the four-user quantum network is selected to evaluate the long-term stability of the deployed system. Both the coincidence rate and the Bell-state fidelity remain stable over 1.5 hours of continuous operation, demonstrating the stability of the source and deployed fiber network.



Supplementary Figure 4. **Representative unstable operation of polarization-entangled photon-pair generation in the deployed fiber network.** Two representative measurements (**a** Alice - Charlie and **b** Alice - Bob) exhibiting temporal fluctuations are shown. The gradual drift in coincidence rate is primarily attributed to variations in chip-to-fiber coupling caused by laboratory temperature fluctuations, as the photonic chip and lensed fibers are mounted on separate stages. Despite the substantial variation in coincidence rate, the measured Bell-state fidelity remains stable, indicating that the entanglement quality is robust against moderate coupling drifts.



Supplementary Figure 5. **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.



Supplementary Figure 6. **Transmission of DWDM channels.** The DWDM has a channel spectral bandwidth of 0.3 nm. In Fig.3f,g of the main text, the joint spectral intensity (JSI) mapping is performed using 16 channel pairs with a spacing of 100 GHz. The channel crosstalk is measured to be below -20 dB.