

Supplementary information: A flexible and resource-efficient quantum network enabled by integrated photonics

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S1 Laser chip

The self-injection locked dual-external-cavity laser (SIDECL) is a III-V/Si₃N₄ hybrid integrated laser designed to provide two wavelength channels required by the mode-pairing quantum-key-distribution (MP-QKD) network. As shown in Figure S1a, two independently driven InP reflective semiconductor optical amplifiers (RSOAs), with gain spectra centered in the C-band, are coupled to a low-loss Si₃N₄ extension chip

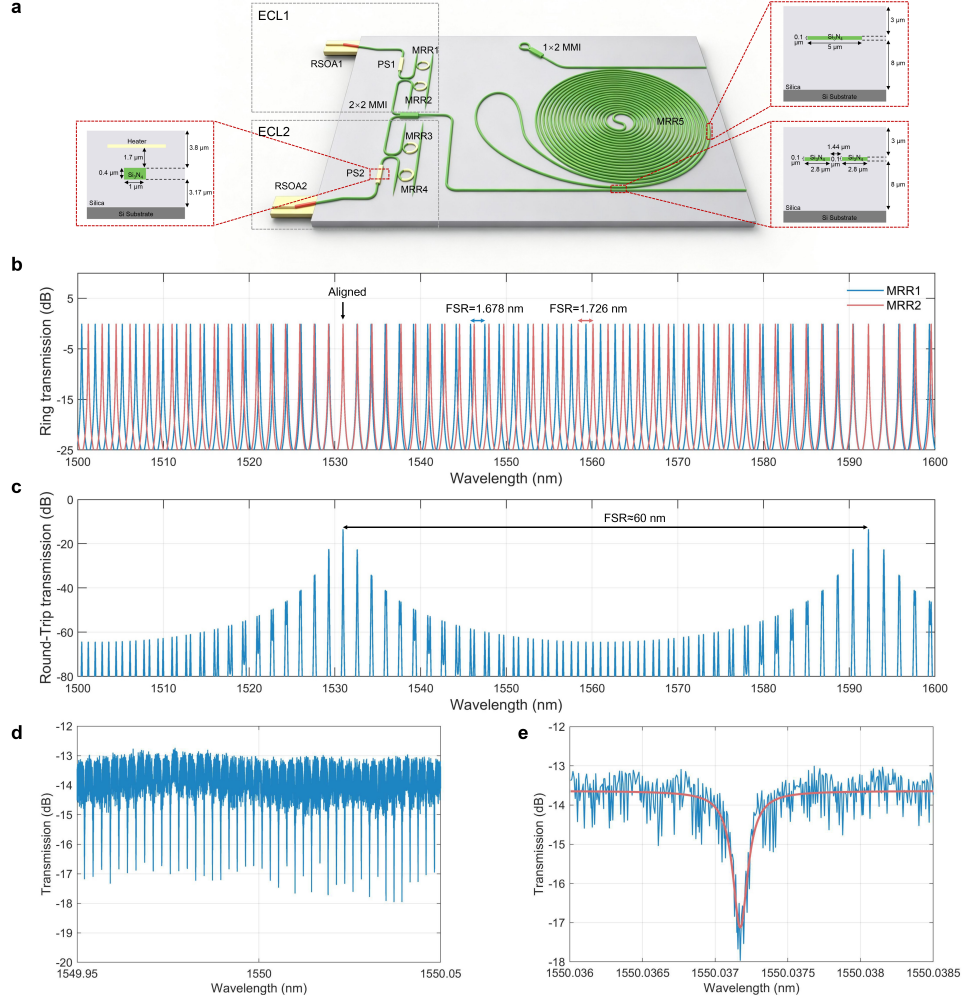


Fig. S1 **a** Cross-sectional schematic of the SIDECL chip. **b** Simulated add-drop transmission spectra of MRR1 and MRR2. **c** Simulated round-trip transmission spectrum of the external cavity. **d** The transmission spectrum of the MRR5. **e** Lorentzian fitting of one resonance.

via two lenses. The rear facet of each RSOA is coated with a high-reflection film with a reflectivity of approximately 90%. The RSOA waveguide at the coupling facet is tilted by 6° with respect to the surface normal and coated with an anti-reflection film to suppress parasitic reflections. The Si_3N_4 waveguide is 400 nm thick and 1 μm wide, with top and bottom cladding thicknesses of 3.8 μm and 3.17 μm , respectively. The metallic heater is positioned above the waveguide, separated from it by 1.7 μm . Inverse-taper spot-size converters narrow the waveguide from approximately 1 μm to 0.29 μm , expanding the mode area and reducing the coupling loss to below 2.5 dB per

facet. Each RSOA is paired with two cascaded add-drop-type microring resonators (MRRs) forming a Vernier filter: MRR1-MRR2 select the wavelength of ECL1 and MRR3-MRR4 select the wavelength of ECL2. For a MRR of circumference L and group index n_g , the free spectral range (FSR) is given by:

$$FSR = \frac{\lambda^2}{n_g L} \quad (S1)$$

MRR1 and MRR2 have circumferences of 720.221 μm and 700.215 μm , corresponding to FSRs of 1.678 nm and 1.726 nm, respectively. MRR3 and MRR4 have the same circumferences as MRR1 and MRR2, respectively. Figure S1b shows the transmission spectrum of the two MRRs. The two resonance combs are therefore slightly mismatched, preserving the aligned resonance peaks while suppressing the misaligned peaks and expanding the effective FSR shown in Figure S1c. The resulting effective FSRs are about 60nm:

$$FSR_{Vernier} = \frac{FSR_1 \cdot FSR_2}{|FSR_1 - FSR_2|} \quad (S2)$$

The measured tuning range of each ECL is approximately 57 nm, which is slightly different from the theoretical analysis. Thermal tuning changes the alignment of the two resonances and provides the coarse wavelength adjustment, whereas PS1 and PS2 on the bus waveguide compensate for the round-trip phase of the two external cavities. The two laser outputs are then combined using a 2×2 multimode interferometer (MMI).

A single ECL cannot provide sufficient relative-frequency stability between the lasers belonging to two communicating users. Self-injection locking (SIL) suppresses laser phase noise by feeding the laser into a high-Q resonator to generate feedback. Both ECLs are therefore coupled to a common ultra-high-Q microring, MRR5, placed in a Sagnac-assisted feedback loop. When a Vernier-selected longitudinal mode is aligned with one resonance of MRR5, resonant backscattering returns narrowband optical feedback to the corresponding ECL and establishes SIL. The high-Q resonator increases the effective photon lifetime and suppresses phase noise, while the Vernier filters of two ECLs continue to determine the two wavelengths independently. Theoretical analysis of the SIL shows that the linewidth-suppression ratio is inversely proportional to the square of the loaded Q factor of the MRR5. Multimode waveguides are used to reduce the overlap between the optical mode and the sidewalls, thereby lowering the propagation loss in MRR5. To suppress higher-order-mode excitation while maintaining a compact footprint, MRR5 incorporates Euler bends with maximum and minimum radii of $R_{max} = 2000 \mu\text{m}$ and $R_{min} = 240 \mu\text{m}$. The gap between bus waveguide and MRR5 is about 1.44 μm and the coupling coefficient is simulated to be 0.1. MRR5 has a circumference of 66.5 cm. Its weak bus coupling and long, low-loss optical path together produce a high-Q-factor. Figure S1d shows the transmission spectrum of the MRR5, which has an FSR of 287.5 MHz near 1550 nm. Figure S1e is the Lorentzian fitting of one resonance, with a full width at half maximum (FWHM) of approximately 0.071 pm and a loaded Q factor of approximately 2×10^7 .

The optical spectra were measured using an optical spectrum analyzer (AQ6370D-12, Yokogawa) with a 0.02 nm wavelength resolution. The frequency-noise spectra were

measured using an optical noise analyzer (A0040A, SYCATUS). The laser spectrum generally has a Voigt-like profile arising from $1/f$ noise, which contributes a Gaussian component, and quantum-limited white noise, which contributes a Lorentzian component. The Lorentzian linewidth (intrinsic linewidth), derived from the frequency-noise spectrum[1], is given by:

$$\Delta\nu_{\text{intrinsic}} = \pi S_v^0 \quad (\text{S3})$$

where S_v^0 denotes the power spectral density of the white frequency noise. The white frequency-noise floors of ECL1 and ECL2 are $0.41 \text{ Hz}^2/\text{Hz}$ and $0.30 \text{ Hz}^2/\text{Hz}$, respectively, yielding intrinsic linewidths of 1.29 Hz and 0.94 Hz, respectively. The integral phase is calculated from the frequency-noise spectrum as follows:

$$\varphi_{\text{int}}(\nu) = \int_{\nu}^{\infty} \frac{S_v(f)}{f^2} df \quad (\text{S4})$$

where φ_{int} denotes the integral phase and S_v is the frequency-noise power spectral density. The integral linewidth, $\Delta\nu_{\text{integral}}$, is defined by $\varphi_{\text{int}}(\Delta\nu_{\text{integral}}) = 1/\pi$ and is calculated to be 1.31 kHz and 0.80 kHz, respectively.

S2 Modulator chip

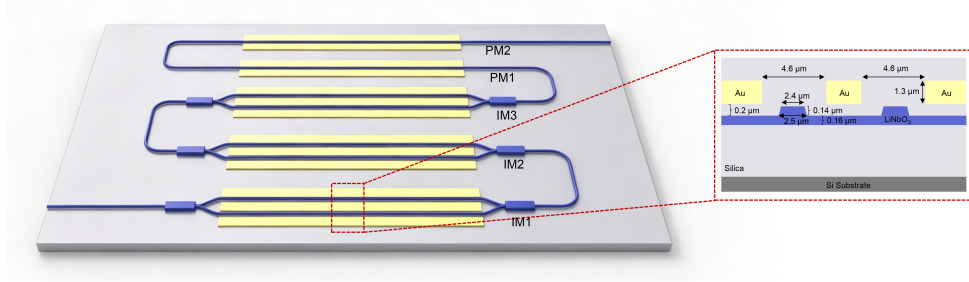


Fig. S2 Cross-sectional schematic of the TFLN modulator chip.

The thin-film lithium niobate (TFLN) modulator chip at each user terminal receives either of the continuous-wave carriers from the SIDECL chip and converts them into the pulsed, intensity-controlled and phase-randomized states required by MP-QKD. As shown in Figure S2, the chip is fabricated on a 300-nm-thick X-cut TFLN film and comprises input and output edge couplers, low-loss waveguides, three Mach-Zehnder intensity modulators (IM1-IM3) and two phase modulators (PM1-PM2). Each IM is implemented as a balanced Mach-Zehnder interferometer with 3-dB splitters and combiners. The ridge waveguide has a width of 2.4 μm and an etch depth of 140 nm, which are selected to balance optical confinement, propagation loss and electro-optic overlap. The modulation arms are driven in a push-pull configuration, while coplanar travelling-wave electrodes provide impedance matching and microwave-optical velocity matching; the electrode length is 11.6 mm and the electrode gap is 4.6

μm . TiN heaters positioned above the IM arms establish the required bias points. The packaged fiber-to-fiber insertion loss (IL) is approximately 25 dB, and heater tuning provides an extinction ratio of approximately 32 dB. The packaged 3-dB electro-optic bandwidth is characterized using a vector network analyzer. The measured electro-optic responses of all IMs are presented in Figure S3 and show bandwidths above 20 GHz. During MP-QKD operation, an arbitrary waveform generator provides the electrical waveforms for IM1-IM3 and PM1-PM2, with a nominal slot duration of 400 ps and a repetition rate of 625 MHz. The modulated output is subsequently attenuated to the single-photon level and launched into the fiber channel.

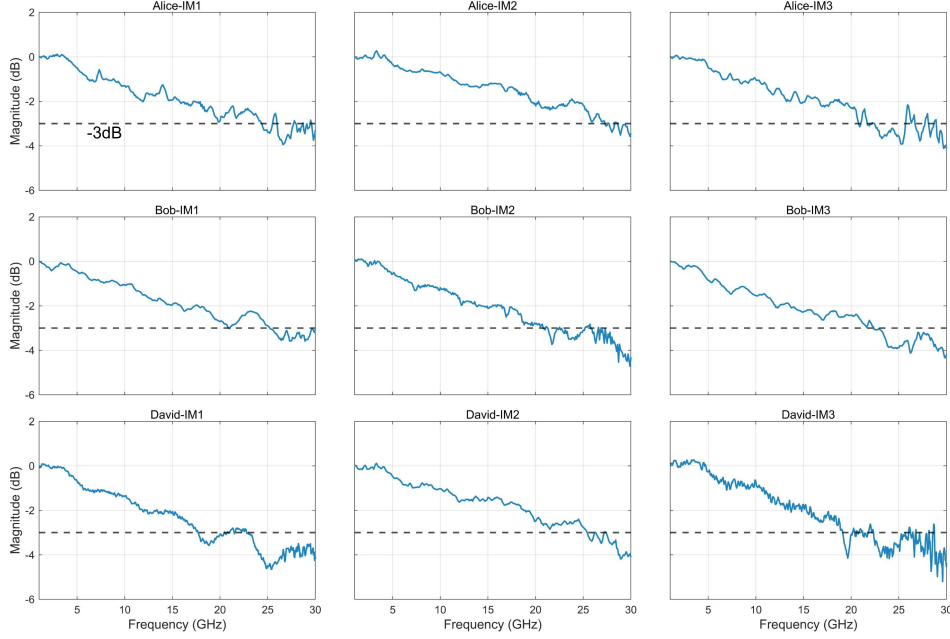


Fig. S3 Electro-optical bandwidth of the IM on all TFLN modulator chips.

S3 Switch chip

S3.1 Architecture and routing matrix of the WSS chip

Each microring switching element (SE) operates as a wavelength-selective add-drop unit. The element consists of cascaded double-ring resonators coupled between an input bus and an output bus. In the unbiased state, the MRR is detuned from the target wavelength channels. The input optical signal therefore remains in the through path, and the drop port is suppressed, as shown in Figure S4a.

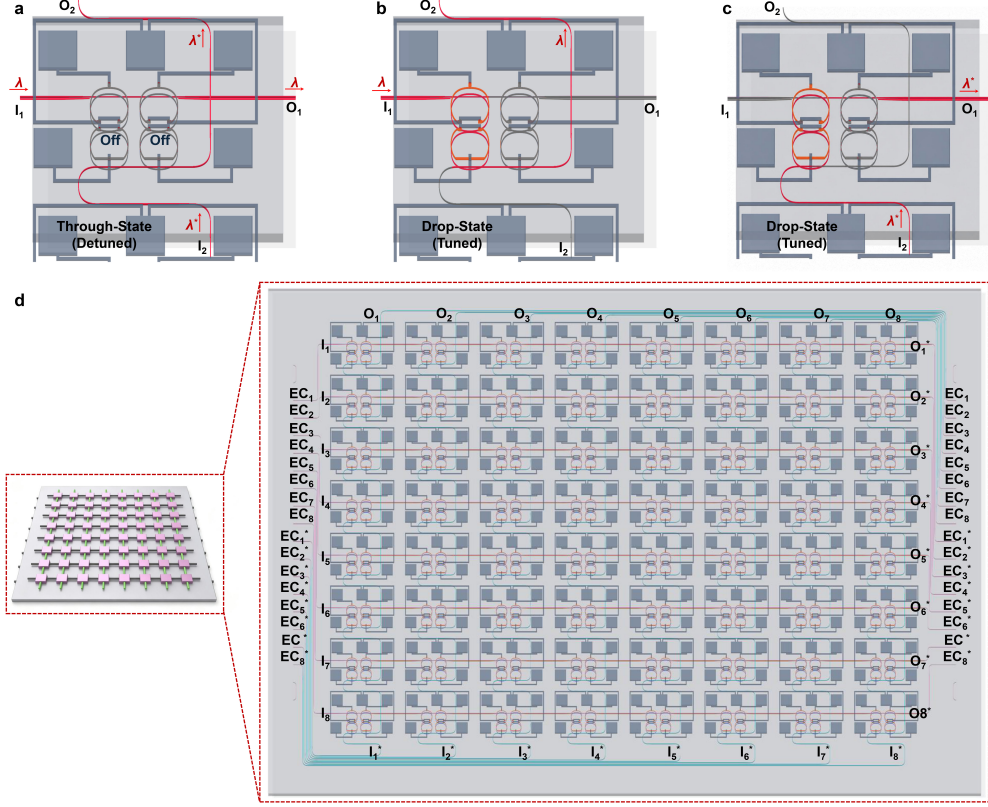


Fig. S4 **a** Through state of a microring SE. When the cascaded double-ring resonators are detuned from the operating wavelength, the input signal remains in the through path and is not dropped to the output bus. **b-c** Drop state of the SE. When electrical power is applied to the integrated TiN heater, the resonance of the selected double-ring resonator is red-shifted to the target wavelength channel, allowing the resonant signal to be dropped from the input bus to the selected output bus. **d** Layout-level routing topology of the WSS organized by crossbar architecture.

When electrical power is applied to the integrated TiN microheater, the microring resonance is both aligned to a selected wavelength channel λ . Under this condition, the selected wavelength channel is dropped from the input bus to the output bus, whereas non-resonant wavelength channels remain in the through path. This provides local wavelength-selective control of a connection between one input bus and one output bus, as illustrated in Supplementary Figures S4b and c.

The 8×8 WSS organized by crossbar architecture is formed by arranging microring SEs at the intersections between eight input buses and eight output buses, as shown in Figure S4d. The element at the intersection of input bus I_i and output bus O_j is denoted as S_{ij} , where $i, j \in \{1, 2, 3, \dots, 8\}$. Activating S_{ij} at a target wavelength λ_k

establishes the wavelength-selective route $Ii(\lambda_k)-Oj$. The routing state of the WSS can therefore be represented by a wavelength-dependent crossbar matrix:

$$S_{ij}(\lambda_k) = \begin{cases} 1, & \lambda_k \text{ dropped from } Ii \text{ to } Oj \\ 0, & \text{otherwise} \end{cases} \quad (\text{S5})$$

For a given network configuration, only a subset of the crosspoints is thermally tuned. These activated crosspoints define the wavelength-port routing map of the WSS. The remaining SEs stay in the unbiased through state. This crossbar architecture allows the WSS to electrically reconfigure the mapping between input ports, wavelength channels and output ports without changing the user-side wavelength allocation.

S3.2 Three-dimensional coupled-resonator SE

Each 2×2 SE in the wavelength-selective switch (WSS) was designed as a vertically integrated Si - Si_3N_4 - Si_3N_4 coupled-resonator add-drop unit. The element consists of a bottom silicon input bus waveguide, two cascaded Si_3N_4 MRRs and a top layer Si_3N_4 output bus waveguide. The two Si_3N_4 resonators are placed in the same middle layer Si_3N_4 layer, while the input and output buses are vertically separated from the resonators to enable three-dimensional (3D) vertical optical coupling.

The optical response of the SE is determined by three local power coupling coefficients, K_1 , K_2 and K_3 , which describe the coupling strengths of the three corresponding coupling regions. Specifically, K_1 is the power coupling coefficient between the bottom silicon input bus waveguide and the first Si_3N_4 MRR, K_2 is the inter-ring power coupling coefficient between the two Si_3N_4 MRRs, and K_3 is the power coupling coefficient between the second Si_3N_4 MRR and the top Si_3N_4 output bus waveguide. The nominal values used in the coupled-ring design are $K_1 = 0.6^2$, $K_2 = 0.1922^2$, and $K_3 = 0.62^2$. These three coefficients independently set the input coupling, inter-resonator coupling and output coupling of the cascaded double-ring add-drop element, thereby determining the drop-port IL, passband bandwidth and out-of-band rejection. In the transfer-matrix calculation, K_i is treated as a power coupling coefficient and is converted to the corresponding field coupling coefficient $k_i = \sqrt{K_i}$, with the corresponding field-amplitude transmission coefficient given by $t_i = \sqrt{1 - K_i}$. This conversion is required because the coupled-resonator spectral response is calculated from coherent field amplitudes rather than optical powers.

A TiN microheater is integrated above the resonators. Applying electrical power to the heater red-shifts the resonances of the coupled rings and aligns the SE to the selected wavelength channel. In the detuned (“off”) state, the operating wavelength channels remain in the through path. In the tuned (“on”) state, the selected resonant wavelength is dropped from the input bus to the output bus.

S3.3 Waveguide-stack and layout-defined Euler-ring geometry

The SE uses a vertically integrated three-layer optical waveguide stack. The bottom silicon waveguide serves as the first bus and has a thickness of 220 nm and a width of 250 nm. The two MRRs are implemented in the middle Si_3N_4 layer using 400-nm-thick and 1- μ m-wide Si_3N_4 waveguides, while the 400-nm-thick and 1- μ m-wide top

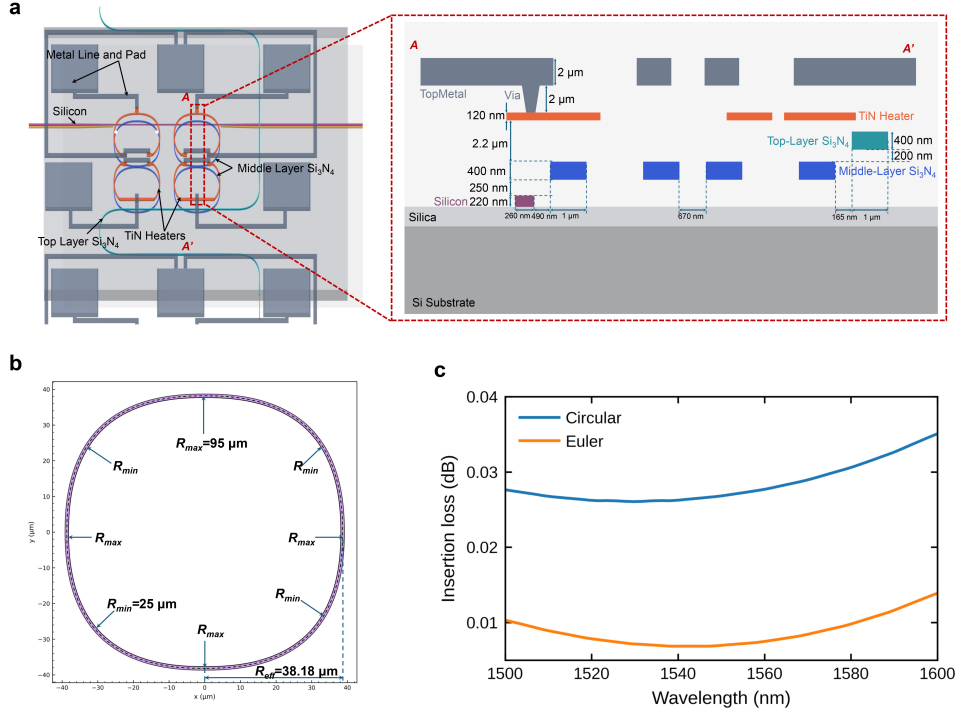


Fig. S5 **a** 3D layout and cross-sectional schematic of the cascaded double-ring SE. The dashed line indicates the cross-section shown on the right, where the vertical waveguide stack, heater, via and top-metal layers are illustrated. **b** Center-line geometry of the Euler-bend rounded microring. **c** Simulated insertion loss of a 90° Euler bend and a 90° circular bend with the same geometrical equivalent radius ($R_{eff}=38.18 \mu\text{m}$) over the 1500~1600 nm wavelength range.

Si₃N₄ waveguide serves as the second bus. The two Si₃N₄ resonators have identical geometrical parameters.

The three local coupling regions are defined by their corresponding waveguide pairs and coupling gaps. The silicon bus is coupled to the first Si₃N₄ ring with a lateral gap of 490 nm and a vertical separation of 250 nm. The two Si₃N₄ rings are laterally coupled with an inter-ring gap of 670 nm. The second Si₃N₄ ring is coupled to the top Si₃N₄ bus with a lateral gap of 165 nm and a vertical separation of 200 nm. The top view and crosssection of the two microring are shown in Figure S5a.

Each Si₃N₄ resonator is designed as an Euler-bend microring, as shown in Figure S5b. The complete ring consists of eight 45° Euler-bend sections and two 1-μm length straight Si₃N₄ coupling sections. Two adjacent 45° Euler-bend sections form one 90° turn. The local bend radius varies between $R_{max}=95 \mu\text{m}$ and $R_{min}=25 \mu\text{m}$. The coupling regions are placed at the flattest part of the ring, corresponding to $R_{max}=95 \mu\text{m}$, where the local curvature is minimized. The corresponding minimum and maximum curvatures are $\frac{1}{R_{max}}$ and $\frac{1}{R_{min}}$.

To evaluate the bending-loss advantage of the Euler geometry, we compared a 90° Euler bend with a 90° circular bend having the same geometrical equivalent radius $R_{eff}=38.18\text{ }\mu\text{m}$. As shown in Figure S5c, the simulated IL of the 90° Euler bend remains below that of the circular bend across the 1500~1600 nm wavelength range. Around the 1550-nm operating wavelength, the Euler bend reduces the bending loss from approximately 2.6×10^{-2} dB for the circular bend to below 1×10^{-2} dB. Therefore, the Euler-bend design provides a compact ring footprint with large FSR while maintaining low bend-induced loss, which is important for reducing the round-trip loss of the cascaded Si_3N_4 microring SE.

S3.4 Initial resonance distribution of the WSS array

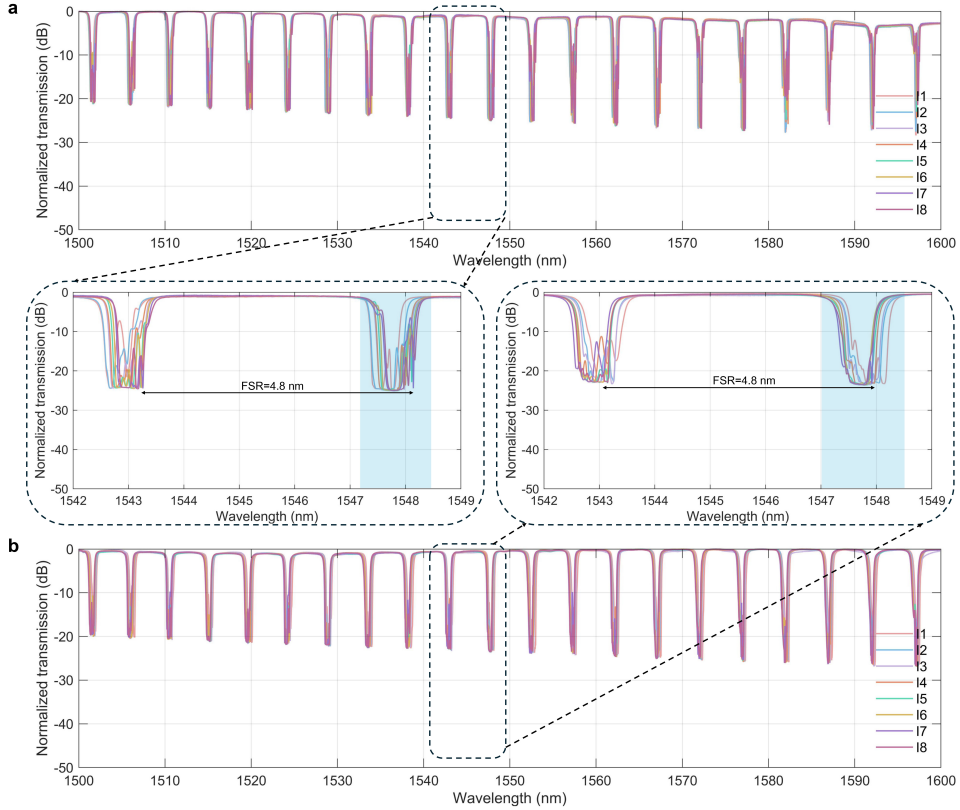


Fig. S6 **a** Passive through-port spectra of the eight silicon input buses. The resonance notches correspond to the initial resonances of the MRRs coupled to the silicon buses. **b** Passive through-port spectra of the eight Si_3N_4 output buses.

We measured the passive through-port transmission spectra of all eight silicon waveguide buses and all eight Si_3N_4 waveguide buses shown in Figure S6. Each bus waveguide passes through the cascaded double-ring SEs along the corresponding row or column of the 8×8 WSS. Therefore, the resonance notches observed in the passive through spectra provide a direct signature of the initial resonance wavelengths of the MRRs coupled to that bus. By combining the through spectra of the eight silicon buses and eight Si_3N_4 buses, the initial resonances of all 128 physical MRRs in the WSS chip can be statistically extracted.

The extracted initial resonance wavelengths of the 128 MRRs are distributed within 1547.233~1548.320 nm, corresponding to a wavelength span of 1.087 nm. The initial resonance distribution occupies only 22.64% of one FSR, whereas, the remaining spectral window within the same FSR is free of initial resonances and can be used for flexible wavelength-channel assignment and thermo-optic tuning. This narrow initial resonance distribution allows the WSS to operate without an initial resonance-trimming step for all MRRs. Selected SEs are tuned to the target wavelength channels only when they are required for a given routing path.

This trimming-free behavior is enabled by the Si_3N_4 resonator platform. The relatively low refractive index of Si_3N_4 , together with the wide 1- μm ring waveguide, reduces the sensitivity of the effective index and resonance wavelength to linewidth variations. As a result, fabrication-induced resonance spread is substantially compressed compared with high-index-contrast, narrow-waveguide SOI platforms.

S3.5 Optoelectronic packaging of the WSS chip

The fabricated WSS chip was optoelectronically packaged to provide simultaneous optical access to the edge couplers and electrical access to the TiN microheaters. The details are provided in Figure S7. The WSS chip contains the 128 microring-resonator switching array in the central region, with edge couplers arranged along the left and right chip facets for fiber-array coupling. Electrical pads for driving the thermo-optic SEs are distributed around the microring array.

Direct wire bonding from the WSS chip to the printed circuit board (PCB) is impractical because of the large number and dense arrangement of heater electrodes. A through-silicon-via (TSV) interposer was therefore used as an electrical fan-out chip. The TSV chip contains three redistribution-layer(RDL) interconnects on the front side and flip-chip pads on the back side. The front-side RDL Pad array routes the dense flip-chip contacts to peripheral wire-bonding pads, enabling electrical connection to the external driving board.

The WSS chip was first flip-chip bonded to the TSV interposer. Solder balls were used to connect the electrical pads of the WSS chip to the flip-chip pads on the back side of the TSV chip. Then, the TSV interposer transfers the electrical signals from the flip-chip interface to the top-side wire-bonding pads through vertical vias and RDL. The peripheral pads of the TSV chip were then wire-bonded to a driving PCB. This packaging scheme separates the dense on-chip heater contacts from the larger-pitch board-level electrical interfaces, allowing independent electrical driving of the WSS SEs while maintaining a compact photonic chip footprint.

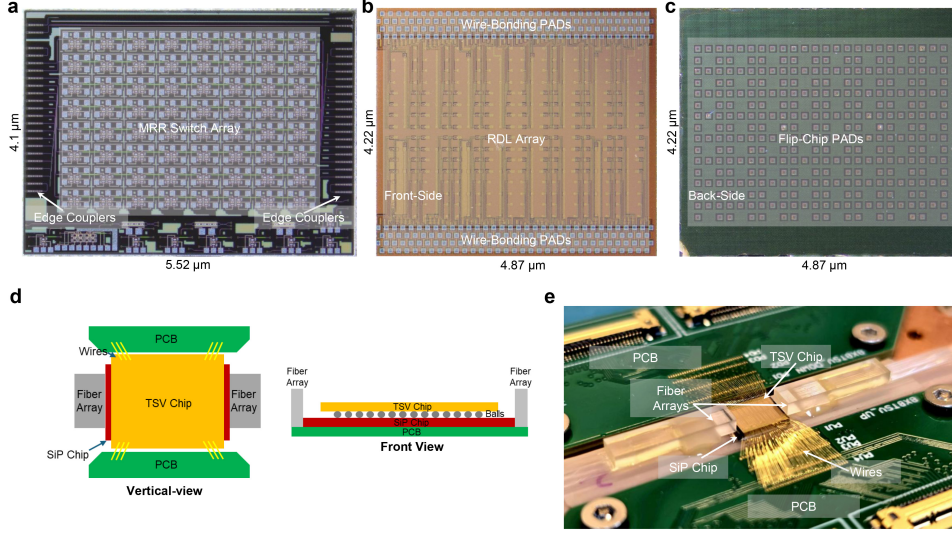


Fig. S7 **a** Optical micrograph of the WSS chip. **b** Front-side micrograph of the TSV interposer. The redistribution-layer array routes the dense flip-chip contacts to peripheral wire-bonding pads. **c** Back-side micrograph of the TSV interposer showing the flip-chip pads used for bonding to the WSS chip. **d** Schematic of the optoelectronic packaging configuration. The TSV interposer is flip-chip bonded to the WSS chip through solder balls. The TSV interposer provides electrical fan-out to the PCB through wire bonds, while fiber arrays are aligned to the edge couplers on both sides of the WSS chip. **e** Photograph of the packaged WSS module, showing the PCB, TSV interposer, silicon photonics (SiP) WSS chip, fiber arrays and wire bonds.

After electrical fan-out, optical packaging was performed by aligning a pair of 20-channel fiber arrays to the edge couplers on both sides of the WSS chip. The WSS chip uses edge couplers located at the chip facets, allowing the input and output waveguides to be coupled to fiber arrays from the left and right sides of the packaged module. The fiber arrays were actively aligned while monitoring the transmitted optical power through selected reference waveguides. After alignment, the fiber arrays were fixed to the chip using optical adhesive to provide stable fiber-to-chip coupling.

S3.6 Full-route spectral characterization of the WSS chip

For each physical route $Ii-Oj$, the corresponding cascaded double-ring SE S_{ij} was thermally tuned to one of the three target wavelength channels: $\lambda_1=1548.776$ nm, $\lambda_2=1549.588$ nm and $\lambda_3=1550.390$ nm. For a given target wavelength λ_k ($k = 1, 2, 3$), a tunable laser was launched into input port Ii , and the heater bias of SE S_{ij} was tuned so that its drop resonance was aligned to λ_k . The output spectra from all eight drop ports $O1, O2, \dots, O8$ were then recorded while sweeping the laser wavelength. This procedure was repeated for all 64 physical routes and for all three employed wavelength channels. For each route state $Ii-Oj$, the target drop port is Oj . The other seven output ports, Om ($m = 1, 2, \dots, 8, m \neq j$) are non-target drop ports. Their residual power was measured to quantify the undesired leakage from the selected route to other

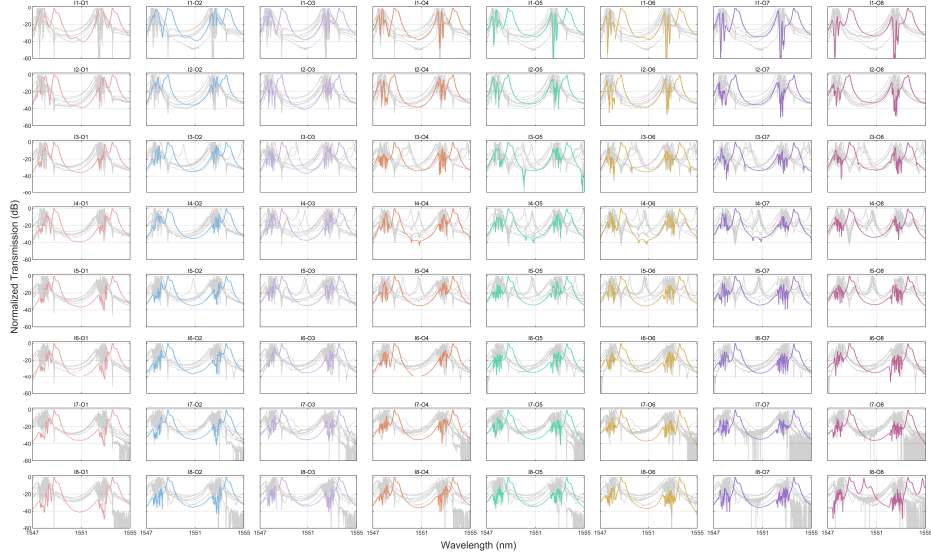


Fig. S8 Measured transmission spectra of all 64 routing paths of the 8×8 WSS at the target wavelength of $\lambda_1=1548.776$ nm. Each subplot corresponds to one routing path and contains the transmission spectra measured from all eight drop ports. The target drop-port spectrum is highlighted, while the non-target drop-port spectra are shown in grey.

drop ports. The full-route spectra measured at the three target wavelength channels are summarized in Figures S8-S10. Each figure corresponds to one target wavelength and contains 64 route-state subplots. In each subplot, the target output port shows a resonant drop response at the selected wavelength, while the other seven output ports quantify the residual leakage to non-target drop ports. From these spectra, the drop-port isolation are extracted for all 64 physical routes at each wavelength channel. At λ_1 , the measured mean isolation across all 64 target drop-port paths ranges from 32.39 dB to 51.08 dB. For λ_2 and λ_3 , the corresponding values are 32.26~55.70 dB and 35.03~56.72 dB, respectively.

The IL distributions of three wavelengths are summarized in Figure S11. At λ_1 , the measured fiber-to-fiber ILs of all 64 target drop paths span 7.3~16.5 dB. The corresponding IL ranges are 5.3~11.5 dB at λ_2 and 6.7~13.0 dB at λ_3 . The overall IL mainly consists of two components: on-chip propagation loss and coupling loss. The on-chip propagation loss range can be referred to in[2], while coupling loss is predominantly governed by fabrication-process quality. Variations in IL among different routing paths of the WSS chip originate from the crossbar architecture, where individual optical links pass through different numbers of MRRs. For instance, the I8-O8 routing path goes through 15 through-state microring elements plus one drop-state element, whereas the I1-O1 path traverses only a single microring element.

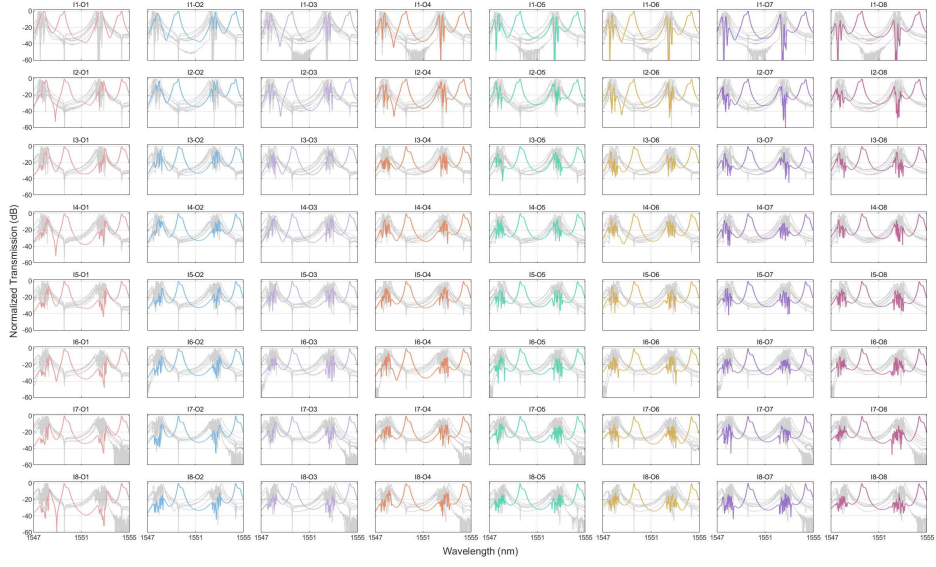


Fig. S9 Measured transmission spectra of all 64 routing paths of the 8×8 WSS at the target wavelength of $\lambda_2=1549.588$ nm.

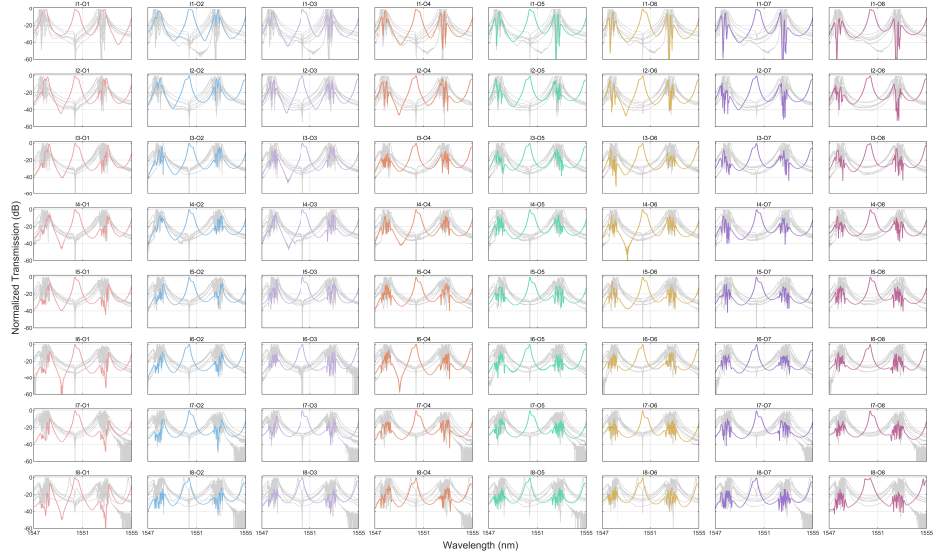


Fig. S10 Measured transmission spectra of all 64 routing paths of the 8×8 WSS at the target wavelength of $\lambda_3=1550.390$ nm.

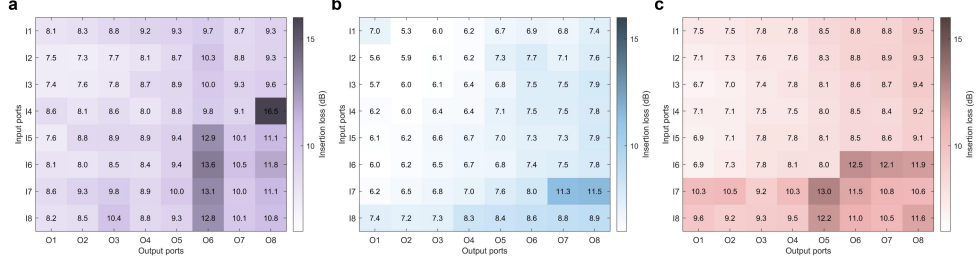


Fig. S11 Measured insertion-loss heatmaps of all 64 routing paths of the 8×8 WSS at target wavelengths: **a** $\lambda_1=1548.776$ nm, **b** $\lambda_2=1549.588$ nm, and **c** $\lambda_3=1550.390$ nm.

S4 Protocol and parameter estimation method

Without loss of generality, we introduce the MP-QKD protocol[3, 4] between two users Alice and Bob, with Charlie as the central measurement node. The same protocol is adopted for all remaining user pairs.

(1) State preparation: During the j -th transmission round ($j = 1, 2, \dots, N$), the two communication parties, Alice and Bob, separately generate coherent states. For Alice, the generated coherent state is denoted as $|e^{i\theta_A^j} \sqrt{\tau_A^j}\rangle$, where the phase θ_A^j follows a uniform distribution within the interval $[0, 2\pi)$. The intensity τ_A^j is chosen from the intensity set $\{\mu_A, v_A, o_A\}$ (satisfying $o_A < v_A < \mu_A$) based on the predefined probability distribution p_{τ_A} . Correspondingly, Bob generates a coherent state $|e^{i\theta_B^j} \sqrt{\tau_B^j}\rangle$ in the same manner. These generated coherent states are then transmitted to the measurement node Charlie through the quantum channel.

(2) Measurement: Charlie adopts single-photon detectors (SPDs) to implement interference measurement on each group of pulse pairs received from Alice and Bob. The detection results are recorded in the form of binary signals: $D_{L(R)} = 1$ means that the left (right) single-photon detector generates a click signal, while $D_{L(R)} = 0$ represents no click. A round is defined as effective only when the XOR result of the two detectors meets $D_L \oplus D_R = 1$, and only the data from effective rounds are retained for subsequent processing.

(3) Mode pairing: After repeating the state preparation and measurement steps until N_{sent} pulses are transmitted, Alice and Bob start the mode pairing process according to the pairing strategy described in Algorithm 1. The maximum interval length of the paired pulses is defined as L_{max} .

(4) Basis sifting: In the basis sifting stage, Alice determines the basis of each paired round according to the intensity information of the paired pulses. For a coincident pulse pair, if the intensity combination is $[\tau_A^j, \tau_A^k] \in \{[\mu_A, o_A], [o_A, \mu_A]\}$, the Z basis is assigned to this pair; if the intensity combination is $[\tau_A^j, \tau_A^k] = [v_A, v_A]$, the X basis is assigned. Bob uses the same basis labeling rule to complete the basis labeling of his own paired rounds.

(5) Key mapping: Key mapping is implemented separately for Z basis pairs and X basis pairs to ensure the consistency of key bits between Alice and Bob. For Z basis pulse pairs, Alice maps the intensity combination $[\mu_A^j, o_A^k]$ to bit 0, and $[o_A^j, \mu_A^k]$ to bit 1. On the contrary, Bob maps $[o_B^j, \mu_B^k]$ to bit 0 and $[\mu_B^j, o_B^k]$ to bit 1. For X basis pairs, the bit value depends on the relative phase $\delta^{jk} = \delta_A^{jk} - \delta_B^{jk}$, where $\delta_{A(B)}^{jk} = (\theta_{A(B)}^j - \theta_{A(B)}^k) \bmod 2\pi$. Only the data of pairs satisfying $|\delta^{jk}| \leq 2\pi/M$ or $||\delta^{jk}| - \pi| \leq 2\pi/M$ are retained for parameter estimation (where M is the number of phase slices and $M = 16$ in our system). Considering the rapid phase drift, the relative phase can be compensated as $\hat{\delta}^{jk} = (\delta^{jk} - 2\pi\Delta f\Delta t) \bmod 2\pi$, where Δf is the frequency offset and Δt is the time separation between the paired clicks. Bob flips his recorded bit if $\hat{\delta}^{jk} = 0$ and different detectors click, or if $\hat{\delta}^{jk} = \pi$ and the same detector clicks twice, ensuring the consistency of the keys between Alice and Bob.

(6) Parameter estimation and postprocessing: After completing key mapping, Alice and Bob use the Z and X basis pair data to estimate the lower bound of the number of single-photon bits n_{11}^Z and the upper bound of the phase error rate e_{11}^{ph} by means of the decoy-state method. After completing parameter estimation, Alice and Bob perform error correction and privacy amplification in sequence, and finally obtain the secure key rate, whose calculation formula is as follows:

$$R = \frac{1}{N_{\text{sent}}} \{ n_{11}^{Z,L} [1 - H(e_{11}^{ph,U})] - f_{\text{EC}} n_{[\mu_A, \mu_B]} H(E_{[\mu_A, \mu_B]}^Z) - \log_2 \frac{2}{\varepsilon_{\text{cor}}} - 2\log_2 \frac{2}{\varepsilon' \hat{\varepsilon}} - 2\log_2 \frac{2}{\varepsilon_{\text{PA}}} \} \quad (\text{S6})$$

where $H(x) = -x\log_2 x - (1-x)\log_2(1-x)$ is the binary Shannon entropy function; f_{EC} is the error-correction coefficient; $n_{[\mu_A, \mu_B]}$ and $E_{[\mu_A, \mu_B]}^Z$ are the total number of pairs and the bit error rate of the Z basis, respectively; ε_{cor} is the failure probability of error correction; ε' and $\hat{\varepsilon}$ are the coefficients of the smooth entropy; and ε_{PA} is the failure probability of privacy amplification.

Here, we present the parameter estimation method for user pair Alice and Bob, which is also adopted by all other user pairs[5, 6]. We adopt the decoy-state method to calculate the lower or upper bounds of single-photon states. Specifically, the lower bound of the number of single-photon pairing events in the Z basis can be derived by the following formula:

$$n_{11}^{Z,L} = \frac{1}{\alpha_{11}} \frac{p_{1|\mu_A} p_{2|\mu_B} p_{0|v_A} p_{0|v_B} n_1 - p_{1|v_A} p_{2|v_B} p_{0|\mu_A} p_{0|\mu_B} n_2}{p_{1|v_A} p_{2|v_B} p_{1|\mu_A} p_{2|\mu_B}} \quad (\text{S7})$$

Algorithm 1 Pairing Strategy

Input: Charlie's announced detection results $D^j = D_L^j \oplus D_R^j$ for $j = 1$ to N ;
maximum pairing interval $L_{\max}$

Output: G pairs; front- and rear- pulse locations of the g -th pair (F_g, R_g) for $g = 1$ to G

```
1:  $g \leftarrow 1$ 
2:  $f \leftarrow 0$ 
3: for  $i = 1$  to  $N$  do
4:   if  $f = 0$  then
5:     if  $D^i = 1$  then
6:        $F_g \leftarrow i$ 
7:        $f \leftarrow 1$ 
8:     end if
9:   else
10:    if  $D^i = 1$  then
11:       $R_g \leftarrow i$ 
12:       $g \leftarrow g + 1$ 
13:       $f \leftarrow 0$ 
14:    else if  $F_g - i \geq L_{\max}$  then
15:       $f \leftarrow 0$ 
16:    end if
17:  end if
18: end for
19:  $G \leftarrow g - 1$ 
```

In this equation, the linear combinations n_1 and n_2 are defined as follows:

$$n_1 = \frac{n_{[\nu_A, \nu_B]}^L}{p_{0|\nu_A} p_{0|\nu_B} P_{[\nu_A, \nu_B]}} - \frac{n_{[o_A, \nu_B]}^U}{p_{0|o_A} p_{0|\nu_B} P_{[o_A, \nu_B]}} - \frac{n_{[\nu_A, o_B]}^U}{p_{0|\nu_A} p_{0|o_B} P_{[\nu_A, o_B]}} + \frac{n_{[o_A, o_B]}^L}{p_{0|o_A} p_{0|o_B} P_{[o_A, o_B]}} \quad (\text{S8})$$

$$n_2 = \frac{n_{[\mu_A, \mu_B]}^U}{p_{0|\mu_A} p_{0|\mu_B} P_{[\mu_A, \mu_B]}} - \frac{n_{[o_A, \mu_B]}^L}{p_{0|o_A} p_{0|\mu_B} P_{[o_A, \mu_B]}} - \frac{n_{[\mu_A, o_B]}^L}{p_{0|\mu_A} p_{0|o_B} P_{[\mu_A, o_B]}} + \frac{n_{[o_A, o_B]}^U}{p_{0|o_A} p_{0|o_B} P_{[o_A, o_B]}} \quad (\text{S9})$$

where $n_{[\tau_A, \tau_B]}$ stands for the count of pairs where the sum of the intensities of Alice's two pulses is $\tau_A = \tau_A^j + \tau_A^k$ and that of Bob's two pulses is $\tau_B = \tau_B^j + \tau_B^k$. The parameter α_{11} is defined as:

$$\alpha_{11} = \frac{1}{p_{[\mu_A, \mu_B]}} \left[\frac{p_{1|\nu_A} p_{1|\nu_B}}{p_{1|\nu_A} p_{2|\nu_B} p_{1|\mu_A} p_{1|\mu_B}} - \frac{1}{p_{1|\mu_A} p_{2|\mu_B}} \right] \quad (\text{S10})$$

Additionally, $p_{[\tau_A, \tau_B]}$ denotes the pairing success probability corresponding to the intensity combination $[\tau_A, \tau_B]$, which can be calculated by:

$$p_{[\tau_A, \tau_B]} = \frac{1}{p_{suc}} \sum_{\tau_A^j + \tau_A^k = \tau_A} \sum_{\tau_B^j + \tau_B^k = \tau_B} p_{\tau_A^j} p_{\tau_A^k} p_{\tau_B^j} p_{\tau_B^k} \quad (S11)$$

In the above formula, p_{suc} represents the total pairing probability, which is expressed as:

$$p_{suc} = \sum_{[\tau_A, \tau_B]} \sum_{\tau_A^j + \tau_A^k = \tau_A} \sum_{\tau_B^j + \tau_B^k = \tau_B} p_{\tau_A^j} p_{\tau_A^k} p_{\tau_B^j} p_{\tau_B^k} \quad (S12)$$

For the X basis, the upper bound of the number of errors in single-photon pairs can be expressed as:

$$m_{11}^{X,U} \leq p_{0|2\nu_A} p_{0|2\nu_B} p_{[2\nu_A, 2\nu_B]} M_{2v} \quad (S13)$$

where the linear combination M_{2v} (representing the number of error pairs in the X basis) is given by:

$$M_{2v} = \frac{m_{[2\nu_A, 2\nu_B]}}{p_{0,2\nu_A} p_{0,2\nu_B} p_{[2\nu_A, 2\nu_B]}} - \frac{n_{[o_A, 2\nu_B]}^U}{2p_{0,o_A} p_{0,2\nu_B} p_{[o_A, 2\nu_B]}} - \frac{n_{[2\nu_A, o_B]}^U}{2p_{0,2\nu_A} p_{0,o_B} p_{[2\nu_A, o_B]}} + \frac{n_{[o_A, o_B]}^L}{2p_{0,o_A} p_{0,o_B} p_{[o_A, o_B]}} \quad (S14)$$

The lower bound of the number of single-photon pairings in the X basis can be estimated with reference to the lower bound $n_{11}^{Z,L}$ of the Z basis, as shown below:

$$n_{11}^{X,L} = \frac{p_{1|2\nu_A} p_{1|2\nu_B} p_{[2\nu_A, 2\nu_B]}}{p_{1|\mu_A} p_{1|\mu_B} p_{[\mu_A, \mu_B]}} n_{11}^{Z,L} \quad (S15)$$

Based on the above parameters, the upper bound of the phase error rate can be further determined by the following formula:

$$e_{11}^{X,U} = \frac{m_{11}^{X,U}}{n_{11}^{X,L}} \quad (S16)$$

In accordance with the random-sampling theory without replacement, the upper bound of the phase error rate can be obtained with a probability of at least $1 - \varepsilon_e$, which is expressed as:

$$e_{11}^{ph,U} = e_{11}^{X,U} + \rho(\varepsilon_e, e_{11}^{X,U}, n_{11}^{Z,L}, n_{11}^{X,L}) \quad (S17)$$

where the function ρ is defined as:

$$\rho(a, b, c, d) = \sqrt{\frac{(c+d)(1-b)b}{cd} \ln \left[\frac{c+d}{2\pi cd(1-b)ba^2} \right]} \quad (S18)$$

The bounds of the expected value are derived from the observed value by means of the Chernoff bound. For example, given an observed value n , the corresponding lower and upper bounds can be established with success probabilities of $1 - \varepsilon^L$ and $1 - \varepsilon^U$, respectively, which are[7, 8]:

$$n^L = \frac{n}{1 + \chi^L}, n^U = \frac{n}{1 - \chi^U} \quad (\text{S19})$$

Here, χ^U and χ^L can be solved by the following equations:

$$\left[\frac{e^{\chi^L}}{(1 + \chi^L)^{1 + \chi^L}} \right]^{\frac{n}{1 + \chi^L}} = \varepsilon^L, \left[\frac{e^{-\chi^U}}{(1 - \chi^U)^{1 - \chi^U}} \right]^{\frac{n}{1 - \chi^U}} = \varepsilon^U \quad (\text{S20})$$

S5 Post-measurement compensation method

Quantum signals transmitted over long fibers are susceptible to phase fluctuations, and remotely deployed lasers inevitably suffer from frequency drifts. These non-ideal factors introduce additional quantum bit error rates (QBERs) in the X basis, thus degrading the performance of the MP-QKD protocol. Fortunately, in hundred-kilometer-scale fibers, the influence of fiber phase fluctuations can be neglected, and the system performance is dominated by the frequency offset between lasers. The QBER of the X basis can be expressed as[9, 10]:

$$E_X = \frac{1 - V_2}{2} + \frac{V_2}{2} \left[1 - e^{-2\pi^2(\sigma_l^2 + \sigma_f^2)\Delta t_0^2} \cos(2\pi\Delta f_0\Delta t_0) \right] \quad (\text{S21})$$

where V_2 denotes the second-order coincidence interference visibility, σ_l is the standard deviation of fiber phase fluctuation rate, σ_f is the standard deviation of laser frequency fluctuation, Δt_0 represents the average pairing time, and Δf_0 is the average frequency offset within the corresponding time. In practical systems, the impact of fluctuation σ_l and σ_f is negligible compared with frequency offset Δf_0 .

To address the issue of frequency drift, we adopt a post-measurement compensation (PMC) method[10] in our system. This scheme does not require strong reference light, and is implemented in the post-processing stage without additional hardware. Notably, the PMC processing is performed concurrently with the preparation and transmission of quantum signals, without publishing any extra information or leaking the encoding phase. Therefore, the security of the original protocol is fully preserved. The principle is described as follows: during post-processing, the response events in the X basis are accumulated, and the frequency offset is estimated by fast Fourier transformation (FFT) method. After interference between Alice's and Bob's pulses, the probabilities of arriving at the SPDs are respectively:

$$p_0(t) = \frac{1}{2} [1 + \cos \delta(t)], p_1(t) = \frac{1}{2} [1 - \cos \delta(t)] \quad (\text{S22})$$

where $\delta(t) = 2\pi\Delta f(t - t_0) + \delta_0$, δ_0 is the original phase difference for $t = t_0$. Then we can get:

$$p(t) = p_0(t) - p_1(t) = \cos \delta(t) \quad (\text{S23})$$

We define the time-domain signal $\{x_n\}$ by encoding the SNSPD responses in each time bin: $x_i = 1$ for only the left detector click $D_L = 1$ and $D_R = 0$, $x_i = -1$ for only the right detector click $D_L = 0$ and $D_R = 1$, and $x_i = 0$ otherwise. After performing FFT on the discrete signal, the frequency component with the maximum amplitude in the spectrum is taken as the estimated Δf . In the experiment, the sampling time bin width is set to 500 ps, and zero-padding is adopted to double the sampling points, which improves the frequency resolution and reduces the estimation error. Finally, for the coincidences of X basis in jk round, the relative phase can be compensated as $\hat{\delta}^{jk} = (\delta^{jk} - 2\pi\Delta f\Delta t) \bmod 2\pi$ with encoding phase difference δ^{jk} .

In practice, the success of frequency estimation depends on the signal-to-noise ratio in the frequency domain, which is determined by the number of accumulated coincidence events. When the counting rate is low, a longer accumulation period is required to improve the signal-to-noise ratio, but this may also increase the computational complexity and estimation error. To balance the estimation success rate and computational complexity, we optimize the sampling interval of FFT. Figure S12 compares X-basis QBER distributions with and without FFT parameters optimization, demonstrating the effectiveness of our optimization strategy for frequency-offset estimation.

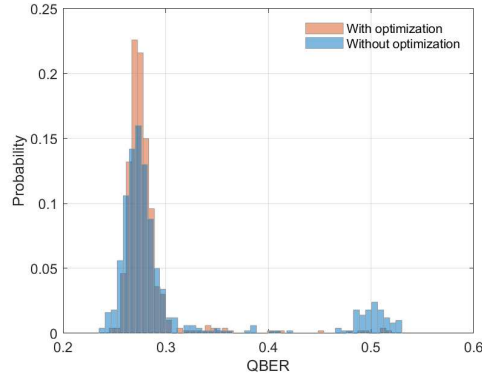


Fig. S12 X-basis QBERs estimation results distribution with and without optimization over a 250 km point-to-point configuration.

S6 Experimental data

References

- [1] Camatel, S., Ferrero, V.: Narrow linewidth cw laser phase noise characterization methods for coherent transmission system applications. *Journal of Lightwave Technology* **26**(17), 3048–3055 (2008)

Table S1 Experimental parameters and results.

Configuration	Symmetric network			Asymmetric network			Point-to-point	
User pair	$A - B$	$A - D$	$B - D$	$A - B$	$A - D$	$B - D$	$A - B$	$A - D$
Distance (km)	100	100	100	125	125	150	200	250
μ_x^1	0.419	0.419	0.419	0.481	0.481	0.406	0.419	0.406
v_x	0.021	0.021	0.021	0.027	0.027	0.023	0.021	0.023
μ_y^2	0.413	0.413	0.413	0.406	0.408	0.408	0.413	0.408
v_y	0.020	0.020	0.020	0.023	0.024	0.024	0.020	0.024
p_{μ_x}	0.241	0.241	0.241	0.205	0.205	0.232	0.241	0.232
p_{v_x}	0.236	0.236	0.236	0.212	0.212	0.217	0.236	0.217
p_{o_x}	0.523	0.523	0.523	0.583	0.583	0.551	0.523	0.551
p_{μ_y}	0.246	0.246	0.246	0.232	0.230	0.230	0.246	0.230
p_{v_y}	0.239	0.239	0.239	0.217	0.210	0.210	0.239	0.210
p_{o_y}	0.515	0.515	0.515	0.551	0.560	0.560	0.515	0.560
F (Hz)	6.25×10^8	6.25×10^8	6.25×10^8	6.25×10^8	6.25×10^8	6.25×10^8	6.25×10^8	6.25×10^8
N_{sent}	1.25×10^{12}	1.25×10^{12}	1.25×10^{12}	6×10^{12}	6×10^{12}	6×10^{12}	1.25×10^{12}	6×10^{12}
L_{max}	10000	10000	10000	10000	10000	10000	10000	10000
$n_{[\mu_x, \mu_y]}$	33013057	32400737	34172905	27631937	27125345	24298782	35618801	28331793
$m_{[\mu_x, \mu_y]}$	158703	165307	204044	166168	168073	119064	228722	174885
$n_{[\mu_x, o_y]}$	31633	33634	39921	25152	25401	22393	45655	25983
$n_{[o_x, \mu_y]}$	32091	32879	42520	22134	22564	21538	46793	23283
$n_{[v_x, v_y]}$	511658	509660	543355	427443	418396	373638	559363	433220
$n_{[v_x, o_y]}$	19649	21898	23157	14164	15069	11461	24071	15903
$n_{[o_x, v_y]}$	20701	19730	22068	12969	12066	12443	26358	17305
$n_{[o_x, o_y]}$	299	332	441	1146	1135	1082	575	1040
$n_{[2v_x, 2v_y]}$	37368	37405	38962	15211	15017	11200	40296	15794
$m_{[2v_x, 2v_y]}$	10082	10077	10360	4317	4205	3349	10727	4522
$n_{[2v_x, o_y]}$	370868	359523	399400	202140	213523	165209	406722	242422
$n_{[o_x, 2v_y]}$	369969	376602	364056	229622	204226	159197	385040	212426
$E_{[\mu_x, \mu_y]}$	0.0048	0.0051	0.0059	0.0060	0.0061	0.0049	0.0064	0.0061
$E_{[2v_x, 2v_y]}$	0.2698	0.2694	0.2659	0.2838	0.2800	0.2990	0.2662	0.2863
$e_{11}^{ph,U}$	0.0882	0.0930	0.0840	0.1488	0.1542	0.1047	0.0830	0.0947
SKR (bpp)	3.74×10^{-5}	3.60×10^{-5}	4.03×10^{-5}	3.71×10^{-6}	3.49×10^{-6}	4.54×10^{-6}	4.14×10^{-5}	5.76×10^{-6}
SKR (bps)	23382.97	22535.64	25237.77	2323.69	2183.81	2842.68	25884.36	3601.98

¹ x denotes the first user in each user pair.² y denotes the second user in each user pair.

[2] Li, X., Gao, W., Lu, L., Chen, J., Zhou, L.: Ultra-low-loss multi-layer 8×8 microring optical switch. *Photonics Research* **11**(5), 712–723 (2023)

[3] Zeng, P., Zhou, H., Wu, W., Ma, X.: Mode-pairing quantum key distribution. *Nature Communications* **13**(1), 3903 (2022)

[4] Xie, Y.-M., Lu, Y.-S., Weng, C.-X., Cao, X.-Y., Jia, Z.-Y., Bao, Y., Wang, Y., Fu,

- Y., Yin, H.-L., Chen, Z.-B.: Breaking the rate-loss bound of quantum key distribution with asynchronous two-photon interference. *PRX Quantum* **3**(2), 020315 (2022)
- [5] Jiang, X.-L., Gao, W., Zhou, Y.-Y., Zhou, Y., Guo, Y.-Y., Lu, Y.-F., Yu, Y.-C., Wang, Y., Li, J.-J., Zhou, C., et al.: A fully-connected chip-integrated reconfigurable mode-pairing quantum key distribution network. *Laser & Photonics Reviews*, 71642 (2026)
 - [6] Xie, Y.-M., Bai, J.-L., Lu, Y.-S., Weng, C.-X., Yin, H.-L., Chen, Z.-B.: Advantages of asynchronous measurement-device-independent quantum key distribution in intercity networks. *Physical Review Applied* **19**(5), 054070 (2023)
 - [7] Lim, C.C.W., Curty, M., Walenta, N., Xu, F., Zbinden, H.: Concise security bounds for practical decoy-state quantum key distribution. *Physical Review A* **89**(2), 022307 (2014)
 - [8] Chau, H.: Decoy-state quantum key distribution with more than three types of photon intensity pulses. *Physical Review A* **97**(4), 040301 (2018)
 - [9] Zhang, L., Li, W., Pan, J., Lu, Y., Li, W., Li, Z.-P., Huang, Y., Ma, X., Xu, F., Pan, J.-W.: Experimental mode-pairing quantum key distribution surpassing the repeaterless bound. *Physical Review X* **15**(2), 021037 (2025)
 - [10] Shao, S.-F., Zhou, L., Lin, J., Minder, M., Ge, C., Xie, Y.-M., Shen, A., Yan, Z., Yin, H.-L., Yuan, Z.: High-rate measurement-device-independent quantum communication without optical reference light. *Physical Review X* **15**(2), 021066 (2025)