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

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Abstract

Quantum key distribution (QKD) is evolving toward large-scale metropolitan networks that interoperate with modern communication infrastructures. Although wavelength division multiplexing (WDM) architectures hold great promise for high secure-key throughput and multi-user access, existing implementations suffer from security vulnerabilities introduced by trusted nodes, limited topological flexibility, and high resource overhead. Here, we experimentally demonstrate a flexible and resource-efficient mode-pairing QKD network enabled by integrated photonics, which natively supports trusted-node-free networking. Each user employs a Hz-level ultra-narrow-linewidth hybrid-integrated laser chip paired with a high-speed thin-film lithium niobate modulator chip

for quantum state preparation, while a silicon-based wavelength-selective switch chip is deployed at the detection center. By introducing a novel global network-management strategy, the network fully decouples conventional physical-topology connections from resource-allocation constraints, allowing dynamic adaptation to time-varying communication demands and dynamic user access/leave. It achieves secure key sharing among all users with at most three distinct wavelengths and N Bell-state measurement units, delivering superior flexible scalability and resource-efficient full-connectivity compared with conventional WDM architectures. In a proof-of-principle three-user network, we achieve secure-key generation over both symmetric and asymmetric metropolitan hundred-kilometer-scale fiber-link configurations. Further point-to-point tests verify secure-key generation over 300 km with the asymptotic key rate exceeding the repeaterless bound. By combining photonic integrated circuits with a favorable network-management strategy, this work provides a chip-scale pathway toward compact, low-cost, and scalable large-scale metropolitan quantum networks.

1 Introduction

Quantum key distribution (QKD)[1–3] has been extensively demonstrated in both laboratory and field scenarios[4–11]. The next major development goal lies in large-scale practical metropolitan quantum networks that can be deeply integrated with 5G/6G communication infrastructures. Among various candidate networking solutions[12–28], wavelength division multiplexing (WDM) networks stand out for their secure-key generation efficiency, link stability, and supported user capacity. They enable the co-transmission of quantum and classical signals over a single shared optical fiber, improving the utilization of existing infrastructures while enhancing the data transmission security of classical optical networks[29–31].

Nevertheless, current WDM quantum networks still face multiple practical limitations. Networking schemes based on trusted nodes introduce inherent security risks[32–38]; communication links are rigidly bound to specific wavelengths[25], hindering adaptation to dynamically changing communication demands; and as users access or leave the network, the demand for wavelength and detection resources changes significantly, resulting in poor resource-utilization efficiency and high network-operation complexity. Collectively, these factors impede the practical deployment of large-scale quantum networks.

Notably, the mode-pairing (MP) QKD protocol[39, 40] natively supports trusted-node-free networking and offers excellent secure-key rate (SKR) performance over long distances[41–44], establishing an ideal protocol foundation for compact, scalable metropolitan quantum networks. However, state-of-the-art MP-QKD demonstrations still rely on high-cost, bulky lasers and discrete modulators. Photonic integrated chips[26, 27, 45–56], with their miniaturization, low-cost, and wafer-scale batch fabrication capability, offer a promising implementation to overcome these hardware-level limitations.

Here, we experimentally demonstrate a flexible and resource-efficient MP-QKD network enabled by integrated photonics. Each user adopts a III-V/Si₃N₄ hybrid-integrated self-injection locked dual-external-cavity laser (SIDECL) chip, capable of simultaneously generating two Hz-level ultra-narrow-linewidth wavelength channels, paired with high-speed thin-film lithium niobate (TFLN) modulator chips with a bandwidth exceeding 20 GHz. The chip-based transmitter design supports parallel transmission of multi-wavelength quantum states and assigns independent wavelength channels to each communicating user pair. At the detection center, an 8×8 silicon-Si₃N₄ three-dimensional (3D) wavelength-selective switch (WSS) chip dynamically reconfigures wavelength-link mappings on demand. To further improve network flexibility and resource-utilization efficiency, we introduce a novel global network-management (GNM) strategy. With this strategy, the overall network connectivity is fully decoupled from rigid constraints on wavelength and detection resource allocation, requiring at most three distinct wavelength channels and N Bell-state measurement units (MUs) to implement secure-key exchange among all users. This unique characteristic endows the network with flexible scalability and resource-efficient full-connectivity, enabling real-time adaptation to time-varying communication demands and dynamic user access/leave. Meanwhile, we implement the MP-QKD protocol with the post-measurement compensation (PMC) method to mitigate the reliance on strong reference light and further reduce the overall system resource overhead. We experimentally demonstrate a proof-of-principle three-user network under both symmetric and asymmetric fiber-link configurations, with average finite-size SKRs of 23.71 kbps and 2.25 kbps over 100 km symmetric and 125 km asymmetric fiber links, respectively. In point-to-point transmission scenarios, SKRs of 25.8 kbps and 3.6 kbps are obtained over 200 km and 250 km symmetric fiber links, respectively, and the asymptotic SKR surpasses the repeaterless Pirandola-Laurenza-Ottaviani-Banchi (PLOB) bound[57, 58] over a 300 km fiber link. Compared with prior trusted-node-free network demonstrations, this work exhibits a distinct advantage in both performance and resource-utilization efficiency. Featuring high integration density, the proposed architecture offers a viable chip-scale route toward practical large-scale quantum networks.

2 Results

2.1 Network Architecture

Fig. 1a illustrates an MP-QKD network consisting of N users, whose user set is defined as $U_1, U_2, \dots, U_N$ ($N \geq 3$). The high-cost single-photon detection modules are centrally deployed at the detection center. Under original network-management strategies, at least N distinct wavelengths are required to avoid signal crosstalk and sustain full-connectivity. Specifically, networks with an odd number of users demand N wavelengths, while networks with an even number of users require $N - 1$ wavelengths. Meanwhile, a total of $N(N - 1)/2$ Bell-state MUs, each comprising beam splitters (BS) and single-photon detectors (SPDs), are necessary to maintain the full-connectivity property. In practical network scenarios, dynamic topology adjustments are frequently encountered, such as user access/leave events, as well as time-varying communication

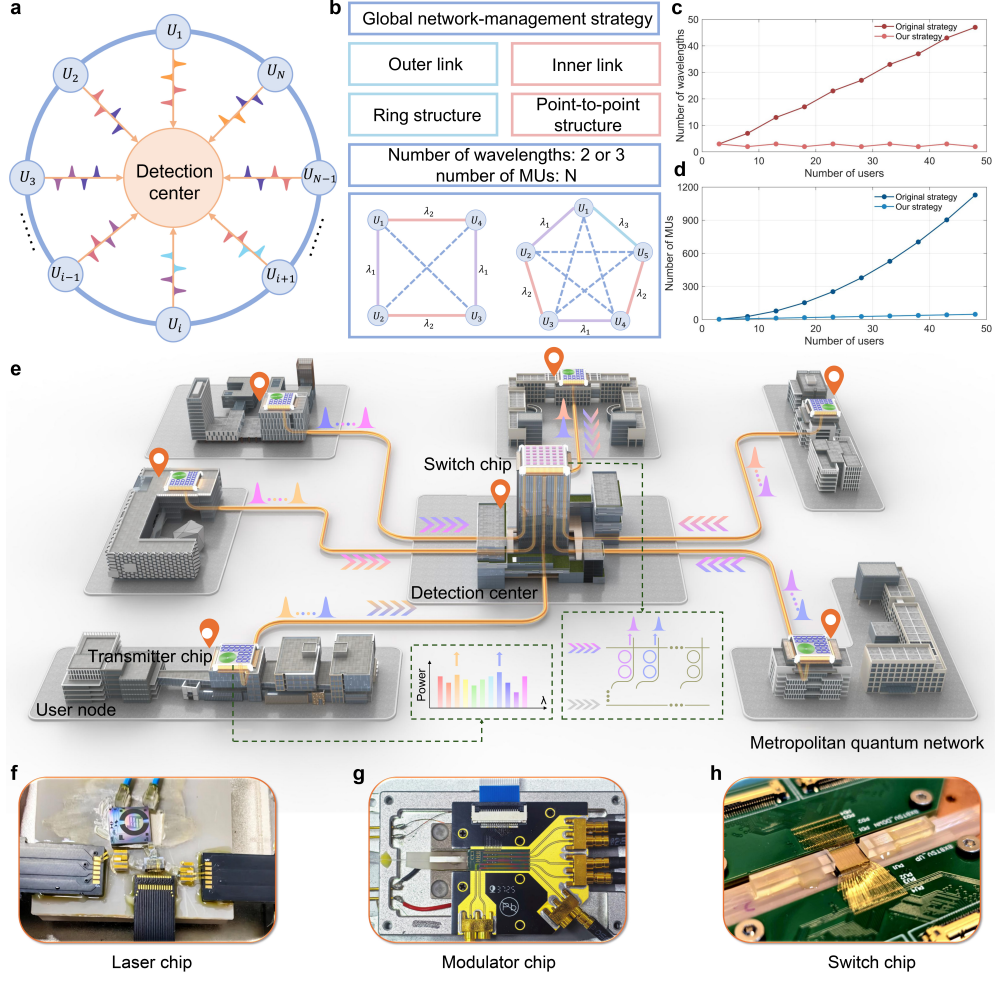


Fig. 1 **a** Schematic diagram of the N -user MP-QKD network. **b** Schematic diagram of the global network-management strategy. **c** The number of wavelengths required for the original strategy and our strategy. **d** The number of MUs required for the original strategy and our strategy. **e** Conceptual diagram of the proposed photonic integrated MP-QKD network architecture. **f-h** Photographs of the core photonic chips: SIDECL chip, TFLN modulator chip, and WSS chip.

demands, including on-demand secure-key distribution for specified high-priority user pairs. Although original WDM networks allocate independent wavelength and detection resources to arbitrary user pairs to perform secure-key exchange, it is strictly limited by the rigid wavelength-port mapping of conventional WDM devices. Any fluctuation in network topology or communication traffic necessitates the reallocation of wavelength and detection resources, leading to limited flexibility and poor resource-utilization efficiency.

To address the above practical challenges, we introduce a GNM strategy, as shown in Fig. 1b. This hybrid networking framework adopts a ring structure for the outer links and a point-to-point structure for the inner links. Representative examples for even ($N = 4$) and odd ($N = 5$) user counts are presented at the bottom of Fig. 1b. Solid lines between users denote assigned wavelength links: networks with an even number of users require only two distinct wavelengths, whereas those with an odd number of users require three distinct wavelengths. Each user simultaneously emits two independent wavelengths over the ring-based network structure using N MUs. The dashed-line connections represent the point-to-point structure where links are not directly connected in the ring structure: without modifying the existing hardware configuration, exclusive wavelength channels and dedicated MUs are no longer pre-allocated for each link. By adopting the available wavelength and MU resources, secure-key sharing can be realized for any user pair to accommodate dynamic communication demands. This strategy is applicable to arbitrary user sizes, and dynamic user access/leave operations introduce no additional signal crosstalk, thereby endowing the network with flexible scalability and resource-efficient full-connectivity. Furthermore, we adopt the PMC method[44] for frequency-offset estimation and phase drift compensation (see Section 5 of the Supplementary Information for details). This approach eliminates the requirements for strong reference light and extra auxiliary hardware modules, thereby further reducing system resource overhead compared with previous MP-QKD systems[24, 41, 43]. As shown in Figs. 1c and 1d, the proposed GNM strategy reduces wavelength resource consumption from N to at most three and transforms the quadratic scaling of MU resources into a linear relationship with the number of users, achieving substantial resource reduction while maintaining scalability and full-connectivity.

Fig. 1e depicts our proposed flexible and resource-efficient MP-QKD network enabled by integrated photonics. Each user utilizes a chip-scale transmitter composed of a hybrid-integrated SIDECL chip and a TFLN modulator chip to implement quantum-state preparation. Through precise frequency locking between its dual external cavities assisted by high-Q microring resonators (MRRs), the SIDECL chip simultaneously outputs two independent continuous-wave (CW) optical carriers with ultra-narrow-linewidths and high side-mode-suppression ratios (SMSRs), satisfying the indistinguishability requirement for high-visibility two-photon interference. The modulator chip is fabricated on a TFLN platform and monolithically integrates intensity modulators (IMs) and phase modulators (PMs) to fully support decoy-state modulation and phase randomization. The left inset of Fig. 1e verifies the broad wavelength tunability and parallel-output capability of each user. The transmitter chip simultaneously emits two wavelengths, satisfying the wavelength requirements of the ring structure for arbitrary user numbers under our GNM strategy. At the detection center, a multi-channel WSS chip serves as the core routing component. Quantum signals delivered through fiber links enter designated input ports and are delivered toward N MUs. According to the configured wavelength and detection resource allocation, the WSS chip routes signals with identical wavelengths from paired users to the same MU, where interference and the resulting detection events are used for key distillation. The right inset of Fig. 1e illustrates that, in contrast to the rigid wavelength-port mapping

of conventional WDM components, the WSS chip can dynamically route input signals at different wavelength to target output ports by leveraging the resonant characteristics of MRRs. When secure-key distribution must be prioritized for non-adjacent high-priority user pairs, the laser chips of the corresponding user pair are tuned to an identical wavelength channel. Through thermo-optic tuning, the WSS chip rapidly reconfigures its routing state to direct these signals to a shared MU. This fulfills on-demand key distribution for arbitrary non-adjacent user pairs with superior resource efficiency. Notably, this capability is difficult to realize in conventional WDM network architectures. Figs. 1f-1h display the photographs of the core integrated photonic chips.

2.2 Chips design

High-visibility quantum interference and multi-user parallel wavelength-division transmission in MP-QKD networks critically depend on laser sources featuring narrow-linewidth and broad wavelength tunability. Although integrated microcombs[25, 26, 28] can deliver multi-wavelength parallel outputs to build communication links for diverse user pairs, they require complex auxiliary control techniques to sustain long-term frequency stability and reliable system operation. Here we design a customized SIDECL chip deployed at each user, which generates two CW optical carriers configurable for independent network link allocation. As illustrated in Fig. 2a, two reflective semiconductor optical amplifiers (RSOAs) are edge-coupled to a low-loss Si_3N_4 chip through inverse-taper spot-size converters with a measured coupling loss below 2.5 dB per facet. Each RSOA is paired with two thermally tunable MRRs, labeled MRR1-MRR2 and MRR3-MRR4, which form independent Vernier filters for ECL1 and ECL2. Thermo-optic phase shifters PS1 and PS2 tune the round-trip phase of each cavity, and 2×2 multimode interferometers (MMIs) multiplex the dual-wavelength outputs. The microscope image of the fabricated SIDECL chip is shown in Fig. 2b. As presented in Fig. 2e, the device achieves a wavelength tuning range of approximately 57 nm with an SMSR exceeding 58 dB. Since the relative frequency drift of lasers between two users must remain sufficiently stable for high-visibility interference, both laser branches are coupled to a shared ultra-high-Q-factor MRR5 in a Sagnac-assisted feedback path. MRR5 features a circumference of 66.5 μm , a free spectral range (FSR) of 287.5 MHz, and a loaded Q factor of 2×10^7 . When the Vernier-selected modes of both ECLs coincide with resonances of MRR5, resonant backscattering returns narrowband optical feedback to the corresponding external cavity. This optical feedback suppresses frequency noise at both operating wavelengths, whereas the Vernier filters retain the capability for independent wavelength tuning of each laser channel. In this way, the laser achieves improved linewidth performance without sacrificing wavelength agility. As shown in Figs. 2f and 2g, the intrinsic and integral linewidths are 1.29 Hz and 1.31 kHz for ECL1, and 0.94 Hz and 0.80 kHz for ECL2, respectively (see Section 1 of the Supplementary Information for details).

Low quantum bit error rates (QBERs) rely fundamentally on high-fidelity quantum state modulation and robust long-term system operation, which impose rigorous demands on modulators with high ER and broad electro-optic bandwidth. Silicon-based modulator chips rely on carrier-based modulation mechanisms, which introduce inherent state-dependent optical loss. The optical attenuation varies with the applied

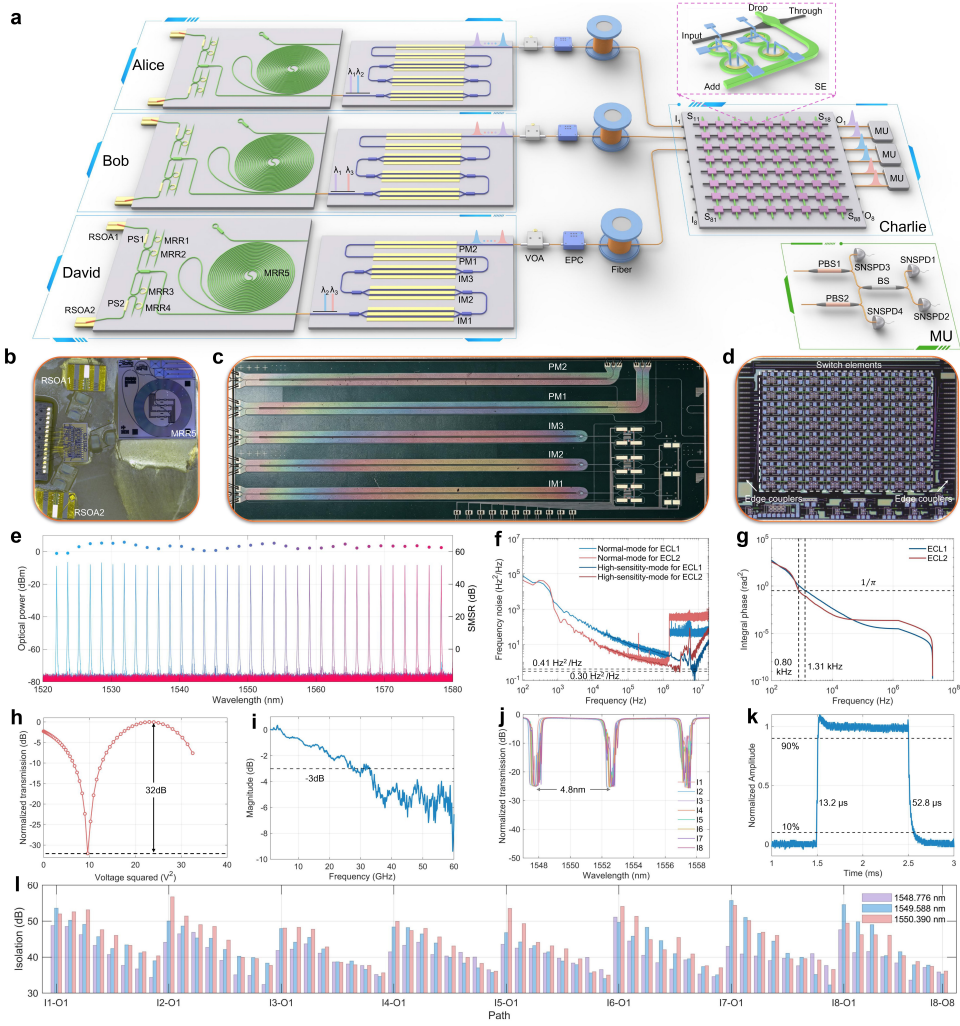


Fig. 2 **a** Schematic of the experimental setup for a three-user photonic integrated MP-QKD network. **b-d** Microscope images of the SIDECL chip, TFLN modulator chip, and 8×8 WSS chip. **e** Measured superimposed lasing spectra and SMSR of the SIDECL chip during coarse wavelength tuning. **f** Measured intrinsic linewidths of ECL1 and ECL2. **g** Measured integral linewidths of ECL1 and ECL2. **h** Normalized optical transmission as a function of voltage squared for the IM1 on the TFLN chip. **i** Electro-optical bandwidth of the IM on the TFLN chip. **j** Transmission spectra of eight through-paths of the WSS chip. **k** Rise time and fall time dynamic responses of the WSS chip. **l** Measured channel isolation across all routing paths under individual injection at three target wavelengths.

modulation voltage and phase condition, distorting the prepared quantum states and elevating the QBER. TFLN offers a low-loss waveguide platform with a strong Pockels effect, enabling high-speed intensity and phase modulation without carrier-induced absorption. To meet the stringent modulation requirements of MP-QKD systems, we design a monolithically integrated high-performance TFLN modulator

chip that enables pulse shaping, decoy-state modulation, and phase randomization for high-quality quantum state preparation. The optical output of SIDECL chip is fiber-connected to a TFLN modulator chip that converts the CW optical carriers into quantum states. The chip integrates three intensity modulators (IM1-IM3) and two phase modulators (PM1-PM2) in a cascaded optical layout. This functional partition separates pulse generation, decoy-state intensity control, and phase randomization while maintaining a compact device footprint. The microscope images of the fabricated TFLN modulator chip are shown in Fig. 2c. The intensity-modulation ER reaches approximately 32 dB shown in Fig. 2h. Integrated microheaters stabilize the optical modulator bias points during long-duration data acquisitions. The modulator electrodes adopt a length of 11.6 mm and a gap of 4.6 μm , yielding a packaged 3-dB electro-optic bandwidth exceeding 20 GHz (Fig. 2i) and half-wave voltages of $V_\pi=2.6$ V. The packaged modulator chip exhibits a fiber-to-fiber insertion loss (IL) of approximately 25 dB (see Section 2 of the Supplementary Information for details).

Multi-user networks require flexible and reconfigurable wavelength routing alongside low-crosstalk parallel channel transmission to support simultaneous key generation among multiple user pairs. Conventional rigid optical devices lack the capability for dynamic channel switching and flexible wavelength resource allocation. To overcome this limitation and enable adaptive network reconfiguration and parallel multi-channel transmission, we fabricate a compact 8×8 silicon- Si_3N_4 3D WSS chip at the detection center to implement dynamic wavelength-link mapping. As illustrated in Fig. 2a, the WSS chip is constructed as a crossbar architecture of 64 independently addressable 2×2 add-drop microring switch elements (SEs). Each SE S_{ij} is positioned at the intersection of horizontal silicon input waveguide I_i and vertical Si_3N_4 output waveguide O_j , enabling wavelength-selective routing from a designated input port to a designated output port via thermo-optic tuning. Fig. 2j presents the transmission spectra of all through ports in the absence of active thermo-optic tuning. The Si_3N_4 microring optical switches exhibit a measured FSR of 4.8 nm, while the closely aligned resonance wavelengths across all channels demonstrate good as-fabricated wavelength uniformity without initial trimming. The rise and fall time of the WSS chip are defined as the 10–90% and 90–10% transition times relative to the steady-state low and high optical levels. The experimentally measured rise and fall times are 13.2 μs and 52.8 μs (Fig. 2k). The overall network reconfiguration latency is jointly determined by the switching time of the WSS chip and other system components, while the μs -scale response of the WSS chip enables rapid reconfiguration of the entire network. Fig. 2l presents the measured isolation across all routing paths at three target wavelengths (1548.776 nm, 1549.588 nm, and 1550.390 nm). The channel isolation ranges from 32.26 dB to 56.72 dB, ensuring sufficient crosstalk suppression for parallel multi-user wavelength multiplexed routing (see Section 3 of the Supplementary Information for details).

2.3 Experimental setup

To validate the feasibility of the presented network architecture and the comprehensive performance of the photonic integrated system, we constructed a proof-of-principle three-user network shown in Fig. 2a. Here, Alice, Bob, and David represent users,

while Charlie denotes the detection center. Each user is equipped with a SIDECL chip and TFLN modulator chip. According to our GNM strategy, $\lambda_{A-B} = \lambda_1 = 1548.776$ nm, $\lambda_{A-D} = \lambda_2 = 1549.588$ nm, $\lambda_{B-D} = \lambda_3 = 1550.390$ nm. The wavelength settings of the SIDECL chips at each user are: A emits λ_1 and λ_2 ; B emits λ_1 and λ_3 , D emits λ_2 and λ_3 . The TFLN modulator chip is driven by an arbitrary waveform generator to produce optical pulse sequences satisfying the MP-QKD protocol requirements. The first-stage IM slices the CW light into pulses with a width of 400 ps and a repetition rate of 625 MHz; the second and third IMs perform decoy-state intensity modulation. Two cascaded PMs implement phase randomization of all optical pulses. The modulator chip is packaged in a metallic enclosure maintained at a stable temperature during all experimental runs. Before entering the fiber channel, quantum signals are attenuated to the single-photon level by a variable optical attenuator (VOA). An electronic polarization controller (EPC) compensates polarization drift accumulated over fiber transmission. After fiber transmission, signals from each user are coupled into the WSS chip which is mounted on a thermoelectric cooler stage to provide active temperature stabilization. A polarization beam splitter (PBS) is deployed at WSS output ports to ensure polarization consistency prior to the MU. Optical pulses interfere at a 50:50 BS, and the resulting interference signals are detected by superconducting nanowire single-photon detectors (SNSPDs). SNSPD1 and SNSPD2 are used for two-photon interference measurements. Polarization controllers are placed before each SNSPD to maximize the detection responsivity, while the system detection efficiency is approximately 70%. The detected events are acquired by a time-to-digital converter and subsequently processed by a central server for post-processing. The other output port of the PBS is connected to SNSPD3 and SNSPD4, whose detection data are used for polarization and time-delay feedback. Real-time system feedback information is delivered to each user via a dedicated Ethernet link.

Based on the above experimental setup, we performed three groups of experiments with the topologies depicted in Figs. 3a-3c. The first experiment corresponds to the symmetric network configuration (Fig. 3a), where users A , B , and D are each connected to the detection center C via a 50 km fiber. At the central node (Fig. 3d), quantum signals from A , B , and D are fed into input ports $I1$, $I2$ and $I3$ of the WSS chip, respectively. Internal SEs S_{11} , S_{16} , S_{22} , S_{23} , S_{34} and S_{35} are activated to keep transmission paths $I1 - O1$, $I1 - O6$, $I2 - O2$, $I2 - O3$, $I3 - O4$ and $I3 - O5$ conductive. Specifically, the two wavelength signals from A are output via ports $O1$ and $O6$; the two wavelengths from B exit through $O2$ and $O3$; the dual wavelengths of D are routed to $O4$ and $O5$. Signals carrying identical wavelengths from distinct users are directed to the same measurement unit for interference measurements. Benefiting from the high channel isolation of the WSS chip, quantum signals on all links propagate exclusively along predefined routes without mutual crosstalk, thus guaranteeing independent parallel communication among multiple users. To verify the flexibility of the network, we assume that the original users leave the network while new users request network access. To emulate a more practical scenario, we consider an asymmetric user distribution case. Fig. 3b shows the asymmetric network configuration, where the fiber lengths from A , B , and D to C are 50 km, 75 km and 75 km. The new users connect input ports $I4$, $I5$ and $I6$ of the WSS chip, respectively. The WSS chip is required

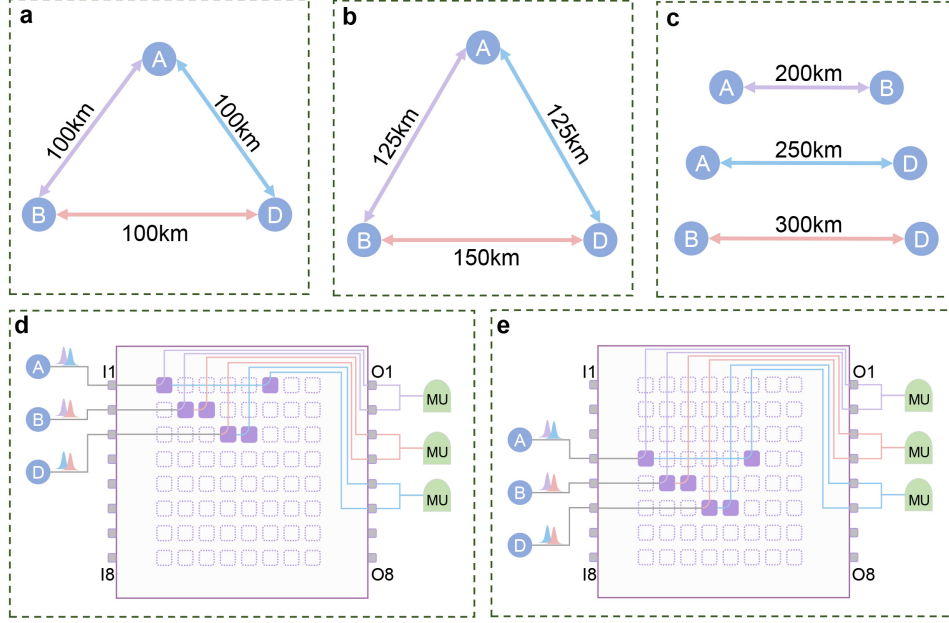


Fig. 3 **a** Symmetric configuration of three-user network. **b** Asymmetric configuration of three new-user network. **c** Point-to-point configuration of three-user network. **d** Wavelength and routing configurations for the symmetric network links in **a**. **e** Wavelength and routing configurations for the asymmetric network links in **b**.

to reconfigure its SEs by transitioning from the previous symmetric network: closing the previously enabled SEs and activating S_{41} , S_{46} , S_{52} , S_{53} , S_{64} and S_{65} . The configuration at the detection center is illustrated in Fig. 3e. To enable stable operation of the MP-QKD protocol over asymmetric fiber links, we optimize the quantum-state modulation intensities and compensate the time-delay across fiber channels, realizing secret key distribution. To independently characterize the long-distance transmission performance of chip-based users, we performed an additional point-to-point experiment without connecting the WSS chip (Fig. 3c). The detailed protocol and parameter estimation method are listed in Section 4 of Supplementary Information.

2.4 System performance

In the experiments, the PMC method was adopted for relative phase estimation and compensation. Specifically, by accumulating and analyzing the X-basis measurement data, the fast Fourier transform (FFT) algorithm was applied to accurately estimate the relative frequency drift between the lasers of the two communicating users, thereby enabling relative phase compensation. In practice, as the channel loss increases, the volume of accumulated valid data decreases correspondingly, leading to an elevated FFT estimation error rate. To address this issue, we optimized the integration window

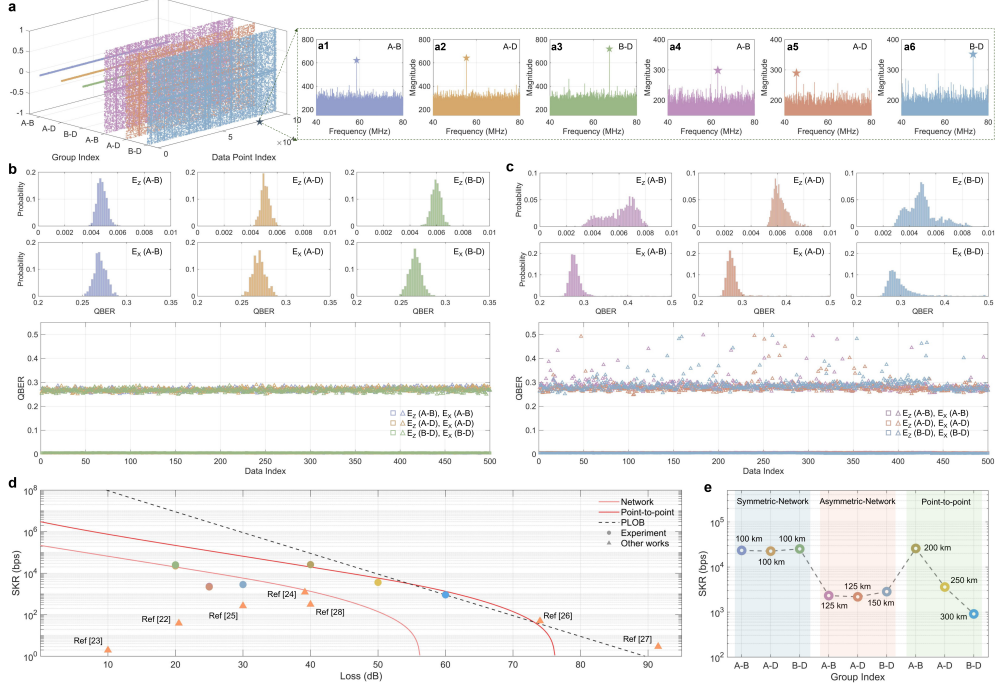


Fig. 4 **a** Distribution of adjacent differences between frequency estimates acquired via successive FFT operations for each user pair. **a1-a3** Frequency distribution of single-shot FFT estimations for each pair in symmetric network configuration. **a4-a6** Frequency distribution of single-shot FFT estimations for each pair in asymmetric network configuration. **b** Z-basis and X-basis QBERs of each user pair in the symmetric network. **c** Z-basis and X-basis QBERs of each user pair in the asymmetric network. **d** SKR in logarithmic scale versus transmission loss between pairwise users, with comparisons to other state-of-the-art trusted-node-free works[22–28]. **e** Measured SKRs in symmetric network, asymmetric network, and point-to-point configurations.

length and triggering threshold of the FFT algorithm, achieving an optimal trade-off between estimation accuracy and efficiency. Fig. 4a presents the distribution of adjacent difference values between frequency estimates obtained by consecutively performing 10^5 FFTs for each user pair within the $[-1, 1]$ interval. This distribution effectively characterizes the stability of consecutive FFT estimations. For the symmetric network configuration, the adjacent difference values are tightly concentrated within $[-0.015, 0.015]$, showing compact distribution and small fluctuations. For the asymmetric network configuration, the difference distributions are more dispersed, indicating degraded FFT estimation stability. Figs. 4a1-4a6 show the frequency distribution of single-shot FFT estimations for each pair. It is clearly observed that under symmetric, low channel loss conditions (Figs. 4a1-4a3), the amplitude difference between the main frequency and sideband frequencies is pronounced. For asymmetric, higher channel loss conditions (Figs. 4a4-4a6), the amplitude gap between the main frequency and sideband frequencies is smaller, which is the primary source of phase estimation errors.

Figs. 4b and 4c plot the QBERs distribution of all user pairs under the X basis and Z basis. Each data point in Fig. 4b corresponds to data accumulated over about 5 s, and those in Fig. 4c are obtained with around 10 s of accumulation. Benefiting from the excellent ER provided by the TFLN modulator chip, the Z basis QBERs of all user pairs are stably controlled within 1%, thereby ensuring the fundamental reliability of key generation. Meanwhile, the laser chip features an ultra-narrow-linewidth and superior frequency stability. Combined with the PMC method, the frequency offset induced by laser frequency differences can be accurately estimated, and the relative phase difference between users can be precisely compensated, so the X-basis QBERs are well distributed between 25% and 35%. Fig. 4b shows results for the symmetric network configuration. The average Z-basis QBER values of pairs $A - B$, $A - D$, and $B - D$ are 0.48%, 0.50%, and 0.59%, respectively. The average X-basis QBERs are 27.01%, 26.96%, and 26.60%. For the asymmetric network configuration, the average Z-basis QBERs of $A - B$, $A - D$ and $B - D$ are 0.69%, 0.60%, and 0.45%. The average X-basis QBERs are 28.82%, 28.07%, and 29.02%. In Fig. 4c, the X-basis QBERs under the asymmetric network setup are generally higher. This phenomenon mainly originates from errors in relative phase difference compensation induced by insufficient valid coincidence counts during PMC processing.

In the symmetric network experiments, 1.25×10^{12} optical pulses were transmitted for each user pair, while 6×10^{12} pulses were allocated to each pair in the asymmetric network experiments. According to the detection results collected by the central network node, the Z-basis data are used for secure key generation, and the X-basis data are adopted for system parameter estimation. The final SKR under the finite-key condition is plotted in Fig. 4d. The light-red curve represents the simulated SKR for the network configuration incorporating the WSS chip and its associated insertion loss; the dark-red curve corresponds to point-to-point SKR results obtained without the WSS chip. The two SKR curves diverge because the introduction of WSS chips brings extra optical loss. Colored scattered points denote the experimental results of different user pairs. As presented in Fig. 4e, at a fiber distance of 100 km, the finite-size SKRs of $A - B$, $A - D$, and $B - D$ reach 23.38 kbps, 22.53 kbps, and 25.23 kbps, respectively. Over 125 km fiber channel, $A - B$ and $A - D$ achieve finite-size SKRs of 2.32 kbps and 2.18 kbps, and $B - D$ obtains 2.8 kbps over a 150 km fiber link. In point-to-point configuration over 200 km and 250 km fiber links, $A - B$ and $A - D$ yield final finite-size SKRs of 25.88 kbps and 3.60 kbps. Moreover, the asymptotic SKR of $B - D$ surpasses the PLOB bound at a symmetric fiber distance of 300 km. Detailed experimental data are summarized in Section 6 of Supplementary Information.

Finally, we further explore user-layer applications of the secret keys obtained in the 100-km symmetric network experiment. Each user encrypts a 600×400 -pixel animal image using corrected keys under a one-time-pad-like scheme and transmits the ciphertext to other users through the public classical channel. As illustrated in Fig. 5, user pairs that distill shared secret keys over the same wavelength successfully realize secret-information sharing.

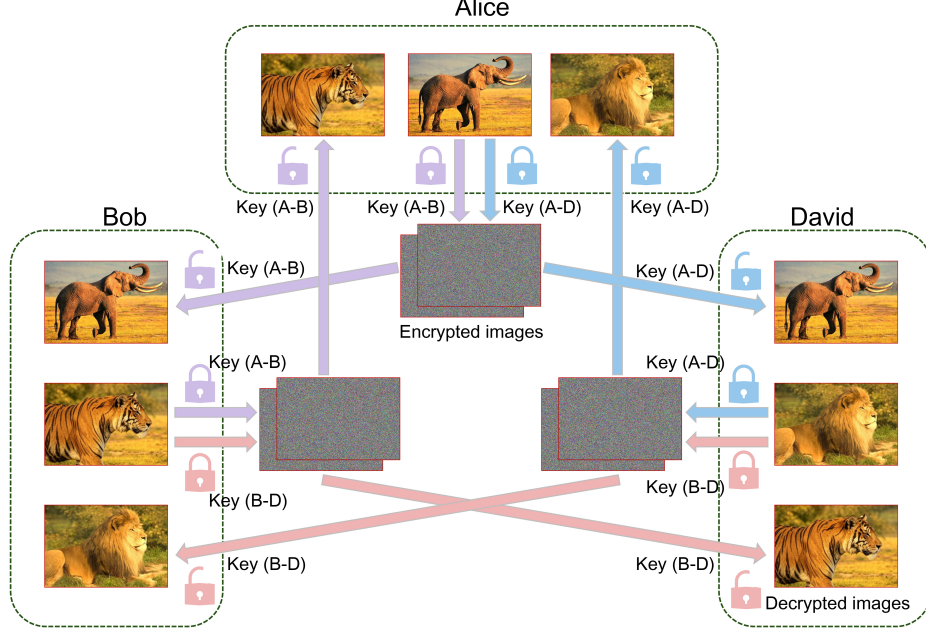


Fig. 5 Each user encrypts a 600×400 -pixel image via a one-time-pad-like scheme and sends the resulting ciphertext over the public classical channel. Paired users with shared secret keys distilled over the same wavelength are capable of performing image decryption.

Table 1 Comparison with prior experimental demonstrations of trusted-node-free networks.

Reference	Protocol Architecture	Photonic integration	Resource overhead ³	Best performance
Tang <i>et al.</i> [22]	MDI	TDM ¹	None	16.5 bps(55 km)
Fan <i>et al.</i> [23]	MDI	PDM ²	None	1.955 bps(50 km)
Zhu <i>et al.</i> [24]	MP	TDM	None	1.217 kbps(195.85 km)
Yan <i>et al.</i> [25]	MDI	WDM	Laser	$N; \frac{N(N-1)}{2}$ 267 bps(150 km)
Zheng <i>et al.</i> [26]	TF	WDM	Laser + Modulator	$N; \frac{N(N-1)}{2}$ 50 bps(370 km)
Zhang <i>et al.</i> [27]	TF	TDM	Laser + Modulator	— 2.93 kbps(540 km)
Wang <i>et al.</i> [28]	MDI	WDM	Laser + Modulator	$N; \frac{N(N-1)}{2}$ 313 bps(200 km)
This work	MP	WDM	Laser + Modulator + Switch	3; N 3.60 kbps(250 km)

¹ Time division multiplexing.

² Polarization division multiplexing.

³ Maximum resource overhead (wavelength; MU) for full-connectivity in WDM networks.

3 Discussion

We compare our results with prior experimental demonstrations of trusted-node-free networks[22–28] in Fig. 4d and Table 1. Against conventional Measurement-device-independent (MDI) QKD systems[22, 23, 25, 28], our work achieves competitive performance in both transmission distance and SKR. These benefits stem from our chip-level implementation of high-performance lasers and modulators, together with the PMC method that guarantees stable MP-QKD operation. When benchmarked against state-of-the-art photonic integrated Twin-Field (TF) QKD networks[26, 27], our finite-size SKRs remain below the PLOB bound, and the maximum secure transmission distance is comparatively limited due to insufficient available coincidence counts under high channel-loss conditions. Nevertheless, owing to our GNM strategy, the system offers a distinct advantage in flexible reconfigurability. Compared with prior full-connectivity WDM architectures, our system exhibits significantly improved resource utilization efficiency.

Beyond the present network demonstration, the combination of the SIDECL, TFLN modulator and WSS paves a practical path from packaged photonic subsystems towards fully integrated quantum networks. In the present implementation, the laser and modulator chips are connected by fiber at each user, and the WSS is packaged separately from the MUs at the detection center. This modular configuration allows the III-V/Si₃N₄ laser, TFLN modulator and silicon-Si₃N₄ switch to be optimized independently, but the remaining fiber-to-chip interfaces increase loss, footprint and sensitivity to polarization and temperature. Because gain, ultra-low-loss resonant feedback and high-speed Pockels modulation are not simultaneously available in a single material platform, a realistic route to a single-chip user encoder is heterogeneous integration. The InP gain sections could be wafer-bonded or transfer-printed above a low-loss Si₃N₄ photonic circuit containing the Vernier filters and shared high-Q feedback resonator, while a bonded TFLN layer provides the cascaded IMs and PMs[59–62]. Adiabatic or vertically coupled interlayer transitions would then transfer laser outputs to the modulators without intermediate fiber coupling. Integrated monitor taps and thermal sensors, together with co-packaged radio-frequency and heater-control electronics, could further stabilize the lasing wavelength, output power and modulator bias. Such integration would therefore reduce not only the physical footprint but also the number of environmentally sensitive interfaces that currently separate state generation, modulation and channel launch.

A similar progression can be envisaged at the detection center. The vertically coupled WSS already acts as a shared photonic backplane for wavelength-link mapping. Its output buses could be connected directly to on-chip 50:50 couplers, phase-control and polarization-diversity circuits, and waveguide-integrated SNSPDs[63–65], so that routing, interference and detection are performed within a common package. Removing repeated fiber-array and discrete-component interfaces would reduce route-dependent IL and path-length drift, both of which become increasingly costly at the single-photon level. Auxiliary monitor photodiodes and closed-loop heater control could provide automated resonance alignment, while a co-packaged electronic controller stores the calibrated wavelength-link mapping and updates the active switching elements as user demand changes[66, 67]. The resulting detection center would remain untrusted from

the protocol perspective, but its optical and electronic functions would be physically consolidated. Furthermore, the WSS-chip-based detection center is no longer restricted to fixed-wavelength channel inputs. This property enables efficient compatibility with existing colorless network architectures[68].

It should be noted that owing to the limited number of available chips and MUs, we cannot experimentally demonstrate network scenarios for larger scales. For reconfiguration, the corresponding SEs are enabled or disabled, and their resonant wavelengths are tuned to match the laser wavelengths, so that identical wavelength signals originating from the target users are directed into the same MU. Such reconfiguration of communication links can satisfy diverse communication demands. Moreover, our scheme cannot achieve secure key sharing for any arbitrary user pair at any time. Instead, the full-connectivity capability is retained: key sharing among all users is realized via the ring structure, whereas secure-key distribution between any two non-adjacent users is performed through the point-to-point structure according to practical communication demands. Our implementation strikes a trade-off between costly resources and network functionalities, which appears to be a cost-effective strategy for deploying large-scale quantum networks.

4 Conclusion

In conclusion, this work proposes a novel flexible and resource-efficient MP-QKD network employing chip-based transmitters and an integrated on-chip switch fabric. Each user integrates an ultra-narrow-linewidth SIDECL chip and a high-speed TFLN modulator chip for quantum-state preparation, while the detection center is equipped with an 8×8 silicon- Si_3N_4 3D WSS chip. Based on our introduced GNM strategy, the network accommodates dynamic variations in network topology and communication tasks while requiring at most three distinct wavelength channels and N Bell-state MUs, thereby offering superior flexible scalability and resource-efficient full-connectivity compared with conventional WDM architectures. We experimentally demonstrated a proof-of-principle three-user network and successfully achieved secret key distribution under symmetric networking, asymmetric networking, and point-to-point transmission scenarios over metropolitan hundred-kilometer-scale fiber links. Featuring high integration density and favorable architecture, this work offers a feasible chip-scale implementation for large-scale deployable quantum networks in the future.

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supervised the project. X.-L.J., X.-H.L., and W.G. wrote the manuscript with the input from all authors.

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References

- [1] Bennett, C.H., Brassard, G.: Quantum cryptography: Public key distribution and coin tossing. *Theoretical Computer Science* **560**, 7–11 (2014)
- [2] Xu, F., Ma, X., Zhang, Q., Lo, H.-K., Pan, J.-W.: Secure quantum key distribution with realistic devices. *Reviews of Modern Physics* **92**(2), 025002 (2020)
- [3] Portmann, C., Renner, R.: Security in quantum cryptography. *Reviews of Modern Physics* **94**(2), 025008 (2022)
- [4] Stucki, D., Legre, M., Buntschu, F., Clausen, B., Felber, N., Gisin, N., Henzen, L., Junod, P., Litzistorf, G., Monbaron, P., *et al.*: Long-term performance of the swissquantum quantum key distribution network in a field environment. *New Journal of Physics* **13**(12), 123001 (2011)
- [5] Sasaki, M., Fujiwara, M., Ishizuka, H., Klaus, W., Wakui, K., Takeoka, M., Miki, S., Yamashita, T., Wang, Z., Tanaka, A., *et al.*: Field test of quantum key distribution in the tokyo qkd network. *Optics Express* **19**(11), 10387–10409 (2011)
- [6] Chen, Y.-A., Zhang, Q., Chen, T.-Y., Cai, W.-Q., Liao, S.-K., Zhang, J., Chen, K., Yin, J., Ren, J.-G., Chen, Z., *et al.*: An integrated space-to-ground quantum communication network over 4,600 kilometres. *Nature* **589**(7841), 214–219 (2021)
- [7] Pittaluga, M., Lo, Y.S., Brzosko, A., Woodward, R.I., Scalcon, D., Winnel, M.S., Roger, T., Dynes, J.F., Owen, K.A., Juárez, S., *et al.*: Long-distance coherent quantum communications in deployed telecom networks. *Nature* **640**(8060), 911–917 (2025)
- [8] Chen, H.-Z., Li, M.-H., Wang, Y.Z., Zhao, Z.-G., Ye, C., Li, F.L., Chen, Z., Han, S.-L., Tang, B., Miao, Y.J., *et al.*: Implementation of carrier-grade quantum

- communication networks over 10000 km. *npj Quantum Information* **11**(1), 137 (2025)
- [9] Pirandola, S., Andersen, U.L., Banchi, L., Berta, M., Bunandar, D., Colbeck, R., Englund, D., Gehring, T., Lupo, C., Ottaviani, C., *et al.*: Advances in quantum cryptography. *Advances in Optics and Photonics* **12**(4), 1012–1236 (2020)
 - [10] Zhou, L., Lin, J., Jing, Y., Yuan, Z.: Twin-field quantum key distribution without optical frequency dissemination. *Nature Communications* **14**(1), 928 (2023)
 - [11] Liao, S.-K., Cai, W.-Q., Handsteiner, J., Liu, B., Yin, J., Zhang, L., Rauch, D., Fink, M., Ren, J.-G., Liu, W.-Y., *et al.*: Satellite-relayed intercontinental quantum network. *Physical Review Letters* **120**(3), 030501 (2018)
 - [12] Fröhlich, B., Dynes, J.F., Lucamarini, M., Sharpe, A.W., Yuan, Z., Shields, A.J.: A quantum access network. *Nature* **501**(7465), 69–72 (2013)
 - [13] Chen, T.-Y., Jiang, X., Tang, S.-B., Zhou, L., Yuan, X., Zhou, H., Wang, J., Liu, Y., Chen, L.-K., Liu, W.-Y., *et al.*: Implementation of a 46-node quantum metropolitan area network. *npj Quantum Information* **7**(1), 134 (2021)
 - [14] Proietti, M., Ho, J., Grasselli, F., Barrow, P., Malik, M., Fedrizzi, A.: Experimental quantum conference key agreement. *Science Advances* **7**(23), 0395 (2021)
 - [15] Park, C.H., Woo, M.K., Park, B.K., Kim, Y.-S., Baek, H., Lee, S.-W., Lim, H.-T., Jeon, S.-W., Jung, H., Kim, S., *et al.*: $2 \times n$ twin-field quantum key distribution network configuration based on polarization, wavelength, and time division multiplexing. *npj Quantum Information* **8**(1), 48 (2022)
 - [16] Wengerowsky, S., Joshi, S.K., Steinlechner, F., Hübel, H., Ursin, R.: An entanglement-based wavelength-multiplexed quantum communication network. *Nature* **564**(7735), 225–228 (2018)
 - [17] Wen, W., Chen, Z., Lu, L., Yan, W., Xue, W., Zhang, P., Lu, Y., Zhu, S., Ma, X.-s.: Realizing an entanglement-based multiuser quantum network with integrated photonics. *Physical Review Applied* **18**(2), 024059 (2022)
 - [18] Ren, S.-Y., Wang, W.-Q., Cheng, Y.-J., Huang, L., Du, B.-Z., Zhao, W., Guo, G.-C., Feng, L.-T., Zhang, W.-F., Ren, X.-F.: Photonic-chip-based dense entanglement distribution. *Photonix* **4**(1), 12 (2023)
 - [19] Joshi, S.K., Aktas, D., Wengerowsky, S., Lončarić, M., Neumann, S.P., Liu, B., Scheidl, T., Lorenzo, G.C., Samec, Ž., Kling, L., *et al.*: A trusted node-free eight-user metropolitan quantum communication network. *Science Advances* **6**(36), 0959 (2020)

- [20] Liu, X., Liu, J., Xue, R., Wang, H., Li, H., Feng, X., Liu, F., Cui, K., Wang, Z., You, L., *et al.*: 40-user fully connected entanglement-based quantum key distribution network without trusted node. *Photonix* **3**(1), 2 (2022)
- [21] 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)
- [22] Tang, Y.-L., Yin, H.-L., Zhao, Q., Liu, H., Sun, X.-X., Huang, M.-Q., Zhang, W.-J., Chen, S.-J., Zhang, L., You, L.-X., *et al.*: Measurement-device-independent quantum key distribution over untrustful metropolitan network. *Physical Review X* **6**(1), 011024 (2016)
- [23] Fan-Yuan, G.-J., Lu, F.-Y., Wang, S., Yin, Z.-Q., He, D.-Y., Chen, W., Zhou, Z., Wang, Z.-H., Teng, J., Guo, G.-C., *et al.*: Robust and adaptable quantum key distribution network without trusted nodes. *Optica* **9**(7), 812–823 (2022)
- [24] Zhu, H.-T., Huang, Y., Pan, W.-X., Zhou, C.-W., Tang, J., He, H., Cheng, M., Jin, X., Zou, M., Tang, S., *et al.*: Field test of mode-pairing quantum key distribution. *Optica* **11**(6), 883–888 (2024)
- [25] Yan, W., Zheng, X., Wen, W., Lu, L., Du, Y., Lu, Y.-Q., Zhu, S., Ma, X.-S.: A measurement-device-independent quantum key distribution network using optical frequency comb. *npj Quantum Information* **11**(1), 97 (2025)
- [26] Zheng, Y., Wang, H., Jia, X., Huang, J., Yuan, H., Zhai, C., Dai, J., Shi, J., Zhang, L., Zhang, X., *et al.*: Large-scale quantum communication networks with integrated photonics. *Nature* **651**(8104), 68–75 (2026)
- [27] Zhang, L., Pan, J., Chen, T.-Y., Li, Z.-P., Lu, Y., Li, W., Pan, W.-X., Ke, W., Guo, Y., Li, W., *et al.*: A photonic integrated long-distance quantum communication network. *Nature Photonics*, 1–7 (2026)
- [28] Wang, F.-X., Zheng, S.-T., Huang, L., Zhang, G.-W., Wang, G.-S., Ding, W.-J., Wang, Z.-H., Wang, S., Yin, Z.-Q., Zou, C.-L., *et al.*: Microcomb-driven large-scale fully connected quantum network. *Nature Communications* (2026)
- [29] Hua, X., Yan, X., He, Q., Han, Y., Luo, M., Yang, C., Zeng, X., Zhang, S., Zhu, Y., Zhang, H., *et al.*: Coexistence of silicon-photonics-based qkd with classical communication over a hollow-core fiber. *Photonics Research* **14**(6), 2469–2479 (2026)
- [30] Dou, T., Gao, S., Li, Z., Tang, J., Xie, Y., Feng, L., Zhang, L., Li, P., Lu, N., Kan, X., *et al.*: 40 tbps classical communication coexistence with quantum key distribution over hundred-kilometer hollow-core fiber. *Photonics Research* **14**(4), 1658–1669 (2026)

- [31] Lukens, J.M., Peters, N.A., Qi, B.: Hybrid classical-quantum communication networks. *Progress in Quantum Electronics*, 100586 (2025)
- [32] Lo, H.-K., Curty, M., Qi, B.: Measurement-device-independent quantum key distribution. *Physical Review Letters* **108**(13), 130503 (2012)
- [33] Braunstein, S.L., Pirandola, S.: Side-channel-free quantum key distribution. *Physical Review Letters* **108**(13), 130502 (2012)
- [34] Ma, X., Razavi, M.: Alternative schemes for measurement-device-independent quantum key distribution. *Physical Review A* **86**(6), 062319 (2012)
- [35] Lucamarini, M., Yuan, Z.L., Dynes, J.F., Shields, A.J.: Overcoming the rate–distance limit of quantum key distribution without quantum repeaters. *Nature* **557**(7705), 400–403 (2018)
- [36] Ma, X., Zeng, P., Zhou, H.: Phase-matching quantum key distribution. *Physical Review X* **8**(3), 031043 (2018)
- [37] Wang, X.-B., Yu, Z.-W., Hu, X.-L.: Twin-field quantum key distribution with large misalignment error. *Physical Review A* **98**(6), 062323 (2018)
- [38] Zhou, L., Lin, J., Ge, C., Fan, Y., Yuan, Z., Dong, H., Liu, Y., Ma, D., Chen, J.-P., Jiang, C., *et al.*: Independent-optical-frequency-comb-powered 546-km field test of twin-field quantum key distribution. *Physical Review Applied* **22**(6), 064057 (2024)
- [39] Zeng, P., Zhou, H., Wu, W., Ma, X.: Mode-pairing quantum key distribution. *Nature Communications* **13**(1), 3903 (2022)
- [40] 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)
- [41] Zhu, H.-T., Huang, Y., Liu, H., Zeng, P., Zou, M., Dai, Y., Tang, S., Li, H., You, L., Wang, Z., *et al.*: Experimental mode-pairing measurement-device-independent quantum key distribution without global phase locking. *Physical Review Letters* **130**(3), 030801 (2023)
- [42] Zhou, L., Lin, J., Xie, Y.-M., Lu, Y.-S., Jing, Y., Yin, H.-L., Yuan, Z.: Experimental quantum communication overcomes the rate-loss limit without global phase tracking. *Physical Review Letters* **130**(25), 250801 (2023)
- [43] 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)

- [44] 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)
- [45] Ma, C., Sacher, W.D., Tang, Z., Mikkelsen, J.C., Yang, Y., Xu, F., Thiessen, T., Lo, H.-K., Poon, J.K.: Silicon photonic transmitter for polarization-encoded quantum key distribution. *Optica* **3**(11), 1274–1278 (2016)
- [46] Sibson, P., Kennard, J.E., Stanisic, S., Erven, C., O’Brien, J.L., Thompson, M.G.: Integrated silicon photonics for high-speed quantum key distribution. *Optica* **4**(2), 172–177 (2017)
- [47] Bunandar, D., Lentine, A., Lee, C., Cai, H., Long, C.M., Boynton, N., Martinez, N., DeRose, C., Chen, C., Grein, M., *et al.*: Metropolitan quantum key distribution with silicon photonics. *Physical Review X* **8**(2), 021009 (2018)
- [48] Zhang, G., Haw, J.Y., Cai, H., Xu, F., Assad, S., Fitzsimons, J.F., Zhou, X., Zhang, Y., Yu, S., Wu, J., *et al.*: An integrated silicon photonic chip platform for continuous-variable quantum key distribution. *Nature Photonics* **13**(12), 839–842 (2019)
- [49] Wei, K., Li, W., Tan, H., Li, Y., Min, H., Zhang, W.-J., Li, H., You, L., Wang, Z., Jiang, X., *et al.*: High-speed measurement-device-independent quantum key distribution with integrated silicon photonics. *Physical Review X* **10**(3), 031030 (2020)
- [50] Semenenko, H., Sibson, P., Hart, A., Thompson, M.G., Rarity, J.G., Erven, C.: Chip-based measurement-device-independent quantum key distribution. *Optica* **7**(3), 238–242 (2020)
- [51] Avesani, M., Calderaro, L., Schiavon, M., Stanco, A., Agnesi, C., Santamato, A., Zahidy, M., Scriminich, A., Foletto, G., Contestabile, G., *et al.*: Full daylight quantum-key-distribution at 1550 nm enabled by integrated silicon photonics. *npj Quantum Information* **7**(1), 93 (2021)
- [52] Li, L., Wang, T., Li, X., Huang, P., Guo, Y., Lu, L., Zhou, L., Zeng, G.: Continuous-variable quantum key distribution with on-chip light sources. *Photonics Research* **11**(4), 504–516 (2023)
- [53] Li, W., Zhang, L., Tan, H., Lu, Y., Liao, S.-K., Huang, J., Li, H., Wang, Z., Mao, H.-K., Yan, B., *et al.*: High-rate quantum key distribution exceeding 110 mb s⁻¹. *Nature photonics* **17**(5), 416–421 (2023)
- [54] Bernardi, A., Clementi, M., Bacchi, M., Bolaños, M.R., Congia, S., Garrisi, F., Martellosio, A., Passoni, M., Wrobel, A., Agnesi, C., *et al.*: Gigahertz-rate thin-film lithium niobate receiver for time-bin quantum communication. *Light: Science*

- [55] Du, Y., Li, B.-H., Hua, X., Cao, X.-Y., Zhao, Z., Xie, F., Zhang, Z., Yin, H.-L., Xiao, X., Wei, K.: Chip-integrated quantum signature network over 200 km. *Light: Science & Applications* **14**(1), 108 (2025)
- [56] Jiang, X.-L., Guo, Y.-Y., Zhou, Y.-Y., Zhou, Y., Li, X.-H., Lu, Y.-F., Wang, Y., Li, J.-J., Zhou, C., Li, H.-W., *et al.*: Measurement-device-independent quantum key distribution with hybrid integrated self-injection locking lasers. *Journal of Lightwave Technology* **44**(14), 6050–6060 (2026)
- [57] Pirandola, S., Laurenza, R., Ottaviani, C., Banchi, L.: Fundamental limits of repeaterless quantum communications. *Nature Communications* **8**(1), 15043 (2017)
- [58] Pirandola, S.: End-to-end capacities of a quantum communication network. *Communications Physics* **2**(1), 51 (2019)
- [59] Xiang, C., Guo, J., Jin, W., Wu, L., Peters, J., Xie, W., Chang, L., Shen, B., Wang, H., Yang, Q.-F., *et al.*: High-performance lasers for fully integrated silicon nitride photonics. *Nature Communications* **12**(1), 6650 (2021)
- [60] Beeck, C., Haq, B., Elsinger, L., Gocalinska, A., Pelucchi, E., Roelkens, G., Kuyken, B.: Heterogeneous iii–v on silicon nitride amplifiers and lasers via micro-transfer printing. *Optica* **7**(5), 386–393 (2020)
- [61] Pfeiffer, M.H.P., Liu, J., Raja, A.S., Herter, L., Anderson, M., Liu, Z., Boes, A., Mitchell, A., Kippenberg, T.J.: A heterogeneously integrated lithium niobate-on-silicon nitride photonic platform. *Nature Communications* **14**(1), 3493 (2023)
- [62] Su, J., Yuan, Y., Dai, Y., Sun, A., Ran, S., Gao, W., Liu, W., Liu, Y., Lu, L., Zhang, J., *et al.*: A broadband lithium tantalate-on-silicon nitride heterogeneous modulator for optical and terahertz communications and radar sensing. *Nature Communications* (2026)
- [63] Pernice, W.H., Schuck, C., Minaeva, O., Li, M., Goltsman, G., Sergienko, A., Tang, H.: High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits. *Nature Communications* **3**(1), 1325 (2012)
- [64] Najafi, F., Mower, J., Harris, N.C., Bellei, F., Dane, A., Lee, C., Hu, X., Kharel, P., Marsili, F., Assefa, S., *et al.*: On-chip detection of non-classical light by scalable integration of single-photon detectors. *Nature Communications* **6**(1), 5873 (2015)
- [65] Zheng, X., Zhang, P., Ge, R., Lu, L., He, G., Chen, Q., Qu, F., Zhang, L., Cai, X., Lu, Y., *et al.*: Heterogeneously integrated, superconducting silicon-photonics platform for measurement-device-independent quantum key distribution. *Advanced*

- [66] Li, Y., Poon, A.W.O.: Active resonance wavelength stabilization for silicon microring resonators with an in-resonator defect-state-absorption-based photodetector. *Optics Express* **23**(2), 360–372 (2015)
- [67] Sacchi, E., Zanetto, F., Martinez, A.I., SeyedinNavadeh, S., Morichetti, F., Melloni, A., Sampietro, M., Ferrari, G.: Integrated electronic controller for dynamic self-configuration of photonic circuits. *Light: Science & Applications* **14**(1), 348 (2025)
- [68] Li, Y., Zong, L., Gao, M., Mukherjee, B., Shen, G.: Colorless, partially directional, and contentionless architecture for high-degree roadms. In: *Optical Fiber Communication Conference*, pp. 4–2 (2020). Optica Publishing Group

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