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INTEGRATED PHOTONIC CHIPS FOR QUANTUM KEY DISTRIBUTION IN SECURE OPTICAL NETWORKS

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Abstract. Quantum key distribution (QKD) provides information-theoretically secure communication guaranteed by the laws of quantum mechanics, offering protection against both classical and future quantum computer attacks. However, traditional bulk-optic QKD systems suffer from large size, high cost, poor scalability, and limited integration with existing fiber infrastructure. Integrated photonic chips have emerged as the key enabling technology to overcome these barriers by miniaturizing all critical components — lasers, modulators, interferometers, detectors, and frequency combs — onto millimeter-scale chips compatible with mass manufacturing.

This paper reviews the latest breakthroughs in integrated photonic QKD and presents two state-of-the-art implementations.

Keywords: Quantum key distribution, integrated photonic chips, twin-field QKD, InP photonics, silicon nitride microcomb, silicon photonics, secure optical networks, quantum communication.

Introduction. The rapid development of quantum computers poses a serious threat to current public-key cryptography. Quantum key distribution solves this problem by using single photons or coherent states to generate and distribute encryption keys that are provably secure even against an eavesdropper with unlimited computational power. Since the first QKD demonstration in 1984 (BB84 protocol), systems have evolved from laboratory table-top setups to field trials over hundreds of kilometers. However, practical widespread adoption requires compact, reliable, low-cost, and scalable hardware.

Integrated photonics, particularly platforms based on indium phosphide (InP), silicon (Si), and silicon nitride (Si_3N_4), offers the ideal solution. These materials allow monolithic or hybrid integration of lasers, high-speed modulators, low-loss waveguides, frequency combs, and detectors on a single chip. The result is dramatic reduction in size (from racks to millimeters), power consumption, and cost, while improving stability and reproducibility through wafer-scale fabrication.

In 2026, two landmark achievements have brought integrated photonic QKD to a new level of practicality: the large-scale multi-user network in Nature and the gigabit-rate silicon-photonics system. This paper analyzes these systems in detail, highlights their technical advantages, and discusses implications for secure optical networks.

Principles of QKD and the Role of Integrated Photonics. QKD protocols are divided into discrete-variable (DV) and continuous-variable (CV) categories. DV-QKD (e.g., BB84, twin-field) encodes information in single-photon polarization or phase, while CV-QKD uses quadrature amplitudes of coherent states. Twin-field QKD (TF-QKD, proposed 2018) is particularly powerful because it overcomes the repeaterless bound and reaches distances over 800 km in fiber.

Traditional implementations use discrete bulk components, which suffer from alignment drift, high insertion loss (>10 dB per interface), and poor scalability for multi-user networks. Integrated chips solve these issues by:

- Reducing component count and interfaces (loss <1 dB/cm in SiN waveguides)

Scottish International Conference on Multidisciplinary Research and Innovation – SICMRI 2026

- Enabling precise on-chip phase and polarization control
- Supporting wavelength-division multiplexing (WDM) for dozens of users
- Allowing CMOS-compatible mass production (cost per chip <10 USD at scale)

Large-Scale Integrated TF-QKD Network. Led by Prof. Wang Jianwei (Peking University) and Academician Gong Qihuang, the “Weiming Quantum Chip-Network” is the first demonstration of a fully integrated multi-user TF-QKD system.

Architecture:

- Central server chip on 4-inch Si₃N₄ platform integrates a dark-pulse microresonator frequency comb (Q-factor ~20 million, linewidth 40–60 Hz) hybrid-locked to an InP DFB laser. The microcomb provides 10 phase-coherent wavelength channels (30 GHz spacing).

- 20 client transmitter chips (each $4.6 \times 2 \text{ mm}^2$) fabricated on 3-inch InP wafer with 97.5 % modulator yield. Each client monolithically integrates two DBR lasers, six electro-optic phase modulators, intensity modulators, and variable optical attenuators.

Operation: Clients are divided into groups A and B. The server distributes microcomb lines via backbone fibers. Each client injection-locks its lasers to the reference lines, prepares quantum states using the SNS-TF-QKD protocol, and sends them over up to 185 km upstream fiber. Pairwise QKD is performed sequentially across 10 WDM channels. Phase drifts are tracked with dual-wavelength method (recalibration every 2–20 ms).

Performance:

- Maximum distance per pair: 370 km spooled fiber (exceeding repeaterless PLOB bound)
- Total networking capability: 3,700 km
- Quantum bit error rate (QBER): 3.50–4.17 % at 370 km
- Secure key rates surpass theoretical bounds by up to 251.4 % in some channels
- Wafer-scale uniformity ensures all 20 chips perform identically

This star-topology MDI architecture eliminates detector-side attacks and trusted nodes, making it ideal for metropolitan and national-scale quantum networks.

Gigabit-Rate Silicon Photonics CV-QKD System

Complementary to the long-distance TF-QKD, a silicon-on-insulator (SOI) photonic integrated system achieved 1.213 Gbit/s secret key rate over 10 km standard single-mode fiber at 40 Gbaud/s.

Transmitter chip: Dual-polarization QPSK (DP-QPSK) using traveling-wave carrier-depletion modulators, thermo-optic phase shifters, and polarization beam splitter. Receiver chip: Conjugate homodyne detection with balanced germanium PIN photodiodes (responsivity 0.88 A/W) and tunable Mach-Zehnder interferometers.

The system operates at room temperature, uses polar-code information reconciliation for multi-Gb/s throughput, and provides composable finite-size security against collective attacks. This performance is 3–10 times higher than previous integrated CV-QKD demonstrations and proves that photonic chips can deliver classical-communication speeds while maintaining quantum security.

Challenges and Solutions.

- Phase noise and coherence: Solved by Hz-level microcombs and injection locking.
- Insertion loss: Low-loss SiN waveguides and optimized edge couplers (<2 dB/facet).
- Detector efficiency: Hybrid integration with superconducting nanowire single-photon detectors (SNSPDs) or high-efficiency Ge photodiodes.
- Scalability: Wafer-scale InP and SiN fabrication with >95 % yield.
- Integration with classical networks: WDM compatibility allows simultaneous quantum and classical data transmission.

Applications in Secure Optical Networks

- 6G and beyond: Quantum-secure backhaul for base stations.

Scottish International Conference on Multidisciplinary Research and Innovation – SICMRI 2026

- Data centers: Intra- and inter-data-center links protected against quantum attacks.
- Critical infrastructure: Banks, government, power grids.
- Global quantum internet: Satellite + fiber hybrid networks with chip-based ground stations.

Conclusion. Integrated photonic chips have transformed QKD from laboratory curiosity to practical technology. The 2026 Nature demonstration of a 20-user, 370-km scalable network and the 1.213 Gbit/s silicon-photonics system prove that mass-manufacturable, compact, and high-performance quantum hardware is now available. These advances bring unbreakable encryption closer to everyday use in secure optical communication networks worldwide. Future work will focus on full monolithic server chips, field trials over deployed fibers, and hybrid post-quantum cryptography integration.

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