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Innovations in quantum light sources advance entanglement-based QKD networks

Wei Zhang[1,2*]

[1] *Department of Electronic Engineering, Tsinghua University, Frontier Science Center for Quantum Information, State Key Laboratory of Low Dimensional Quantum Physics, Beijing 100084, China*
[2] *Beijing Academy of Quantum Information Sciences, Beijing 100193, China*

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Quantum key distribution (QKD) guarantees information-theoretic security through the fundamental principles of quantum mechanics. As its matures, QKD networks have achieved long-distance deployment, showing significant advancements in practical quantum-security communication infrastructure [1]. When transitioning to large scale quantum communication networks with complicated topologies, conventional paradigms, which are based on point-to-point QKD links connected by trusted nodes, face technical challenges on achieving scalability and optimizing resource allocation.

Quantum entanglements are important resources for quantum networks. By entanglement distribution among multiple users, networks for various quantum information applications could be implemented. Especially, supported by entangled photon pairs generated by spontaneous parametric down-conversion (SPDC) or spontaneous four-wave-mixing (SFWM), QKD networks with any complicated (even fully connected) logical topology could be supported by simple star-shape physical networks. It provides a promising way to break conventional paradigms of QKD networks. The related researches were significantly boosted after the work of wavelength division multiplexing (WDM) entanglement distribution networks based on broadband quantum light sources [2]. Then, new architectures for large and reconfigurable networks became significant topics focusing much attention. The network size (user number) was highly improved by introducing spatial division multiplexing (SDM) to the network. The topology reconfiguration was realized by introducing optical switches, wavelength-selective switches or on-chip quantum interferences. It is worth noting that these improvements usually come with some compromises on QKD performances and the complexities of network implementation.

Recently, Liu et al. [3] proposed a "pump management" approach to support quantum distribution networks with large scale and complicated topology. It is based on the rich SFWM processes in silicon waveguides when they are pumped by multiple pump lights, by which the generated photon pairs exhibit complex spectral correlations. A quantum network with a specific topology could be naturally formed by allocating photons of different frequencies to different users. The network topology could be adjusted by controlling the frequencies of pump lights. In this work, a fully connected QKD network for 10 users based on energy-time entanglement was established in a time-sharing way using three pump lights. Soon after, Zhu et al. [4] proposed a fully connected polarization-entangled network also based on engineered SFWM processes in silicon waveguides. In this work, more pump lights were used to support fully connected topology directly. Furthermore, two silicon waveguides for

*Corresponding author (email: zwei@tsinghua.edu.cn)

SFWMs and a 2D grating coupler for path-polarization conversion were integrated on the same chip to generate polarization entangled photon pairs. A 6-user network was established by the chip under four pump lights with carefully designed frequencies. Both degenerate and non-degenerate SFWM processes are stimulated to support a fully connected topology with 15 entanglement distribution links. The average fidelity of sharing polarization-entangled states exceeded 92.5%.

In both networks, the entanglement distributions are achieved by sending photons of different frequencies to different users. Hence, their network architectures are quite simple, without complicated designs such as beam splitting, wavelength division and combination, etc. Compared to previous WDM-based networks with N users, which require $O(N^2)$ frequency channels to support a fully connected topology, these two networks only need N frequency channels to support N users. Since frequency channels in the telecommunication band are quite limited, this characteristic is preferred for realizing large-scale entanglement-based QKD networks. Additionally, the waveguides in silicon photonic chips are good nonlinear media for broadband SFWMs. It is natural to integrate these nonlinear media with other key optical devices for entanglement generation and distribution, as shown in ref. [4]. The combination of silicon photonic integration with advanced pumping strategy for SFWM sources offers promising ways to enhance the scalability, functionality and reconfigurability of entanglement-based QKD networks.

While these works show that the rich physical processes in quantum light sources have inspired new ideas for developing large-scale entanglement-based QKD networks, challenges such as unwanted SFWM noise and fiber transmission losses need to be addressed for practical deployments. Future work could integrate micro-resonators to enhance the brightness of quantum light sources and develop quantum repeaters to enable more robust long-distance transmission. Moreover, by introducing coherent pump lights for the SFWM processes, SFWM sources may achieve networks with multi-partite entanglement, supporting advanced multi-user protocols such as quantum conference key agreement and distributed quantum computing. It can be expected that innovations in quantum light sources will become a significant way for advancing future quantum networks.

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