Picosecond-spaced time-entangled photonic qudits on chip and their use for quantum communications

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Abstract: We present a platform for the generation and processing of picosecond-spaced time entangled photonic qudits, based on on-chip interferometers and a spiral waveguide. We apply these states to implement quantum communications over fiber telecom networks.

1. Introduction

Time-entangled photonic qudits are considered among the best candidates to implement robust quantum communications over standard telecom networks [1-4]. These can preserve state coherence even over several kilometers of propagation through a single optical fiber, as well as they enable to increase the secret key rate, information efficiency, noise robustness, and security of quantum communication protocols [1]. For this reason, time-entanglement has been widely explored and exploited to build large scale quantum networks for, e.g., metropolitan quantum teleportation [3,4] and quantum secure communications [1,2]. To further boost the applicability of time-entangled qudits for telecom compatible quantum networks, the use of state-of-the-art GHz modulation techniques is highly desired for quantum state processing [5]. However, time qudits are typically characterized by high spacing between the temporal modes, which is typically much larger than hundreds of picoseconds. This results, in turn, in low bit rates, which hampers the use of time qudits for high-speed quantum communications [6]. This issue can be addressed by increasing the photonic space size (better known as Hilbert space) while keeping a low time-bandwidth product (TBP). However, this is still a challenging task to achieve, given that the current architectures to process time qudits, such as multi-arm interferometers, are affected by phase instability, time inaccuracy, and low processing speeds [2]. This significantly hinders scaling up the time modes while preserving a low TPB. Integrated photonic waveguides [7] offer a stable, compact, and potentially mass-producible platform to tackle these issues.

In this work, we address these limitations by demonstrating a low-loss fiber-coupled, integrated platform allowing the generation and processing of picosecond-spaced time-entangled photonic qudits. Such a platform consists of a cascade of on-chip programmable interferometers and of an integrated Hydex-made spiral waveguide [8,9]. We use this platform for the generation and processing of 2- and 4-level time entangled photon pairs, featuring a time mode spacing of 128 ps and 64 ps, respectively. By making use of standard telecom components, we exploit the generated states for quantum communication applications, such as quantum state propagation over 60km-long fiber network and chip-to-chip entanglement distribution.

2. Methods and results

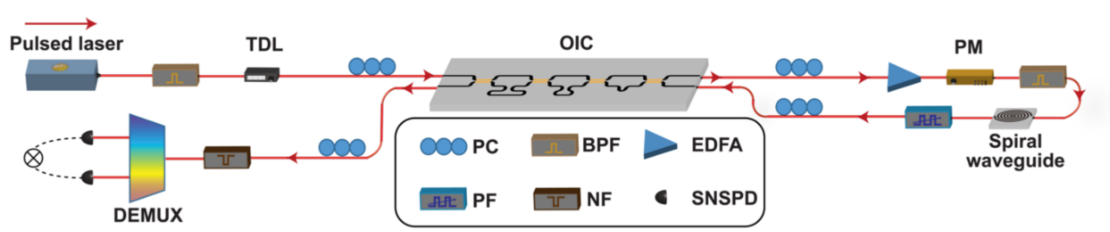

Fig. 1. Experimental setup for quantum state generation and processing. TDL: tunable delay line; OIC: on-chip interferometer cascade; EDFA: erbium-doped fiber amplifier; PM: phase modulator; PC: polarization controller; BPF: band pass filter; NF: notch filter; DEMUX: demultiplexer; SNSPD: superconducting nanowire single-photon detector.

To generate 2-, 4-, and 8-level time-entangled qudits, we configured the programmable on-chip interferometer cascade (OIC) [8,9] to activate one, two, and three interferometers in such a way to create a train of two, four, and eight pulses, respectively. The train was then injected into the spiral waveguide to induce spontaneous four wave mixing and thus generate 2-, 4-, and 8-level time-entangled photon pairs (namely, signal and idler) at telecom bands. The 2-, 4-, and 8-level photon pairs featured a time mode spacing of 128ps, 64ps, and 32ps, respectively, given by the temporal delay between the pulses of the burst exciting the spiral waveguide. For a 200GHz frequency spacing given by dense wavelength-division multiplexing, we could achieve time-entangled photon pairs with TBPs of 0.128ns×200GHz=25.6 and 3×0.064ns×200GHz=35.8 for 2- and 4-level states, respectively. For entanglement verification and quantum state characterization, we performed quantum interference and quantum state tomography measurements. To this end, we processed the generated photon states by making use of a programmable filter, an electro-optic phase modulator, as well as of the same OIC that was used for quantum state preparation. These components allowed us to coherently mix all time modes after arbitrary phase control. For quantum state tomography, we further made use of a frequency-to-time mapping scheme to temporally separate the signal and idler photons, which made it possible to apply different phase modulations for each photon. From quantum interference measurements, we extracted raw (i.e., without background noise subtraction) visibilities of 93.13% and 90.14% in the case of 2 and 4 levels, respectively, that, exceeding the threshold of 70.71% and 81.70% necessary to violate their respective Bell inequality, provided a solid proof for the generation of time entanglement. From quantum state tomography, we estimated fidelities through maximum likelihood estimation, which resulted 98.46% and 84.91% for 2- and 4-level systems, respectively.

We finally tested the suitability and robustness of our platform for quantum communications. To this end, we let both the signal and idler photons propagate each over a 30km fiber system, comprising a 20km single mode fiber, as well as a 10km dispersion compensation fiber module. We verified the preservation of 2- and 4-level time entanglement via quantum interference measurements, from which we extracted visibilities of 96.46% and 89.49%, respectively. We also performed a chip-to-chip quantum communication experiment with two different users. We spatially separated 2- and 4-level signal and idler photons into two different OICs, that is, on Alice's and on Bob's sides. By choosing different phase settings, we measured quantum interferences and extracted visibilities of 89.57% and 92.70% for 2 and 4 levels, respectively.

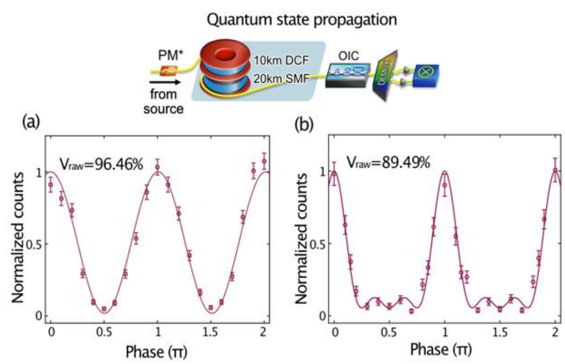

Fig. 2. Quantum state propagation. Signal and idler photons propagate each over 30 kms, thus mimicking two users who are separated by 60 kms. Measured quantum interferences and the extracted respective visibilities for two (a) and four (b) levels. SMF: single mode fiber; DCF: dispersion compensation fiber.

3. Conclusion

The results shown in our work offer a route towards the development and use of time-entangled photonic qudits for robust quantum communications that are compatible with telecom networks and speeds. Our work may pave the way towards quantum secure communication protocols, such as quantum key distribution, between multiple users.

4. References

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