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Telecom-compatible, affordable and scalable quantum technologies

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***Abstract (45 words)*— The realistic implementation of quantum architectures relies on the development of scalable, resource-efficient platforms that are compatible with CMOS technologies as well as fiber networks. This work demonstrates novel schemes utilized for time-/frequency-bin entanglement generation and processing by leveraging existing telecommunications and integrated photonics infrastructures.**

***Keywords*—integrated quantum optics, complex photon states, quantum frequency combs, silicon-based chips, microring resonators, spiral waveguides, integrated Mach-Zehnder interferometers, discrete time and frequency modes, photonic qubits and qudits.**

I. INTRODUCTION

Single and entangled photon states are key resources for many advanced applications, such as quantum secure communications [1], quantum computation and information processing [2]. Thus, the generation first, and the coherent manipulation of these states later, represent a crucial requirement for the development of quantum technologies, which must satisfy current demands of being easy to use, affordable, and scalable. While the low footprint, stability, and new functionalities offered by integrated optics have made it a particularly attractive platform for quantum photonics systems, chip-compatible approaches for the generation and control of complex photon states are highly inaccessible and lack scalability. For example, the on-chip preparation of high-dimensional (qudit) optical entanglement typically requires complex and specialized components. Specifically, d -dimensional frequency-entanglement requires stringent spectral filtering conditions (thus resulting in a significant loss of quantum resources), while time-bin entanglement demands elaborate and stable d -arm interferometers. Integrated quantum frequency combs (QFCs), discrete temporal modes, as well as on-chip and fiber-based interferometers can provide unique solutions to address these issues, as testified by their recent use in quantum optics [3-9].

Here, we present i) an integrated photon pair source (a silicon-based microring resonator [10] platform) to demonstrate the first pulsed quantum frequency comb (QFC) that requires no external laser pumping, as well as the pioneering work featuring the on-chip generation of two- and multi-photon time-bin entangled states [4] and d -level frequency-entangled photon pairs [6]; ii) a suite of tools for the recovery of interferometric phase in fiber-based systems, with specific strategies introduced to maintain the quantum signal-to-noise ratios during entanglement characterization; iii) a scheme for the versatile and coherent control of quantum states that are entangled in the time and frequency degrees of freedom (i.e., d -level cluster states [11]) using only off-the-shelf telecommunications components; and iv) an on-chip Mach-Zehnder interferometer (MZI) and spiral waveguide platform for state preparation/processing (two-level time-bin entanglement) and photon pair generation, respectively.

II. METHODS AND RESULTS

We realized a novel intra-cavity mode-locked excitation scheme that enabled the generation of high-quality pulsed QFCs in a flexible and efficient manner. Specifically, we excited a nonlinear microring resonator using a self-locked, nested-cavity configuration

with an active modulation and investigated the emission statistics of the photon states generated via spontaneous four-wave mixing processes. This was, to the best of our knowledge, the first scheme to generate pulsed integrated QFCs without the need for an external laser. The scheme's versatility and its use of chip-compatible components is a significant step towards implementing a truly compact pulsed QFC source.

We generated time-bin entangled photon pairs through a double-pulse excitation scheme of a microring resonator [10], thus resulting in signal-idler pair generation in a superposition of two discrete time slots (hence, an entangled state), typically characterized using interference techniques. This required MZI platforms developed solely using off-the-shelf telecom components, and which showed ultrastable operating conditions over the entire measurement time (i.e., spanning over weeks/months). For this, we realized a novel strategy that utilized in-phase (passive signal) and quadrature (acousto-optically modulated signal which is orthogonally polarized to the passive signal) phase retrieval methods [12] for real-time phase monitoring and environmental stabilization (Figure 1 (top)). By exploiting such an interferometer, we performed quantum interference measurements of the generated time-bin entangled photons. We extracted a visibility of 82.4% (without background subtraction) that, being higher than the 71% threshold, violates the Bell inequality [13], hence confirming two-photon entanglement.

Taking advantage of the broad phasematching conditions of the microring resonator, we realized d -level frequency-entangled photon pairs, where each photon was intrinsically produced in a 10-level frequency-bin superposition [6]. By using a concatenation of fiber-based components (i.e., programmable amplitude/phase filters and electro-optic phase modulators - EOMs), we were able to coherently control (via phase shifting and frequency mixing) the generated photon states. We confirmed the generation of d -level two-photon entanglement and its quality via quantum interference measurements, for the cases $d = 2, 3$, and 4. We extracted visibilities of 83.7%, 86.6%, and 86.4%, respectively, all violating their respective d -level Bell inequalities [14].

By merging the two approaches for time- and frequency-entanglement generation, we demonstrated a two-photon four-partite three-level cluster state [11] (a complex state exhibiting genuine multipartite entanglement [15]) by exploiting, for the very first time, the concept of hyperentanglement. We transformed such a hyperentangled state into a cluster state by developing and using a controlled-phase gate operation formed by a fiber Bragg grating array and an EOM. We also developed a witness operator [16] for the validation of genuine multipartite entanglement of the realized cluster state.

Finally, we developed a method for the generation and characterization of ultrafast time-bin entangled two-photon qubits by using an on-chip MZI (Figure 1 (bottom)) and a spiral waveguide fabricated on a CMOS-compatible Hydex material platform. The time-bin entanglement was characterized using quantum interference measurements, which resulted in $> 90\%$ raw visibility, thus exceeding the 71% threshold necessary to violate the Bell inequality [13].

The use of scalable, practical, and affordable platforms shows that our approach is versatile towards future applications not only for quantum technologies (e.g., quantum communication and computing) but also for optical telecommunications (as testified by the use of time- and frequency-multiplexing techniques). Finally, the results shown here offer a route towards the development and use of time-bin encoded photon states for quantum applications such as untrusted-sender secure communication, cryptography, and teleportation that are compatible with telecommunication networks and speeds.

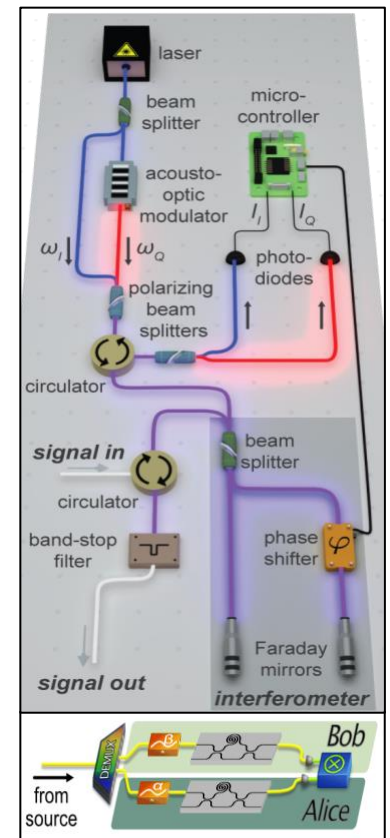


Figure 1. Fiber-based (top) and on-chip (bottom) interferometers for time-bin entanglement generation and processing.

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