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On-chip Quantum State Generation by means of Integrated Frequency Combs

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Entangled photon-pair sources are key building blocks towards the realization of applications in quantum information processing [1], quantum communications [2], as well as imaging and sensing with resolutions exceeding the classical limit [3]. The generation of, e.g. polarization, time-energy and time-bin entangled photon-pairs has been demonstrated using spontaneous parametric down-conversion (SPDC) in nonlinear second-order media, as well as spontaneous four-wave mixing (SFWM) in third-order nonlinear media. Specifically, nonlinear (third-order) interactions in on-chip microring resonators have been widely used to achieve classical frequency combs [4], mode-lock lasers [5], signal processing [6], etc. Integrated photonics can also find applications for quantum state generation in compact, scalable and efficient devices, required for future optical quantum circuits. In particular, solutions focusing on an integrated (on-chip) approach have been recently investigated and developed, including integrated quantum circuits, sources and detectors [7]. In contrast to waveguides, microring resonators [8] with narrow resonances and high Q-factors, offer an improvement in photon-pair generation efficiency, as well as a narrow photon-pair bandwidth, making them compatible with quantum optical devices (e.g. high temporal-resolution single-photon detectors and quantum memories). Most importantly, in contrast to non-resonant waveguides, where individuals photon-pairs, featured by one signal/idler frequency pair, are generally produced, resonant nonlinear cavities (e.g., microring resonators) allow the generation of correlated photon-pairs on multiple signal/idler frequency channels [9], due to their periodic and equidistant resonance structure.

Here, we investigate different approaches to generate optical quantum states by means of integrated optical frequency combs. These include the generation of multiplexed heralded single-photons [9], the first realization of cross-polarized photon-pairs on a photonic chip [10], the first generation of multiple two-photon entangled states [11], and the first realizations of multi-photon entangled quantum states on a photonic chip [11].

The quantum frequency combs were realized by using a 4-port integrated microring resonator with a free spectral range (FSR) of 200 GHz, fabricated in a CMOS-compatible high refractive index silica glass [12]. The resonators were excited with a pulsed mode-locked fiber laser. The high resonator field enhancement and the high nonlinearity allowed generating photon-pairs through SFWM on several frequency channels (corresponding to the ring resonances) symmetrically located with respect to the pump frequency [9]. Depending on the targeted application, different excitation schemes were used. If the pump spectral bandwidth was chosen to be larger than the resonator bandwidth, the laser was spectrally-filtered to excite a single or multiple resonances. The coupling into the resonator then further spectrally filtered the pump to perfectly match the bandwidth of the resonator. This configuration enabled the generation of pure single frequency-mode photons [11]. Coincidence detection was used to characterize the photon coincidence statistics and their temporal duration. We measured the (heralded) second-order coherence of the emitted photons using a Hanbury Brown and Twiss setup. In order to create time-bin entangled photons, an unbalanced phase-stabilized Michelson interferometer generating double pulses was used before the chip. If the pump power was then set to generate no more than one photon-pair per double pulse on average, the photon-pairs were created in a coherent superposition of two discrete time-bins, thus forming an entangled state [11]. To verify entanglement through quantum interference, we added interferometers with the path length difference matched to the first interferometer. Using coincidence detection, this setup allowed to measure quantum interference and perform full quantum state tomography, which characterize the entangled photon-pairs and multi-photon states.

By simultaneously exciting two orthogonal-polarization mode resonances, we introduced a new type of SFWM to the toolbox of integrated photonics [10]. In particular, we demonstrated the first realization of type-II SFWM that allows to directly generate orthogonally-polarized photon-pairs on a chip [10]. We measured photon coincidences, and also drive the system to optical parametric oscillation, generating orthogonally-polarized beams.

Using double pulse excitation, we demonstrated time-bin entangled photon-pairs over the entire frequency comb spectrum [11]. We measured the violation of a Bell-like inequality through quantum interference [13] both on co-, as well as cross-polarized photon-pairs. Performing quantum state tomography [14], we confirmed qubit entanglement with fidelities above 85%, enabling the implementation of quantum information processing protocols [15]. We repeated tomography measurements after 40 km of fiber propagation, and confirmed that the quantum states are well preserved during propagation. This opens up possible implementations in quantum communications applications.

Finally, we achieved the generation of multiple photon-pairs on different frequency mode pairs simultaneously. By measuring four-photon coincidences, quantum interference and tomography, we confirmed the generation of four-photon time-bin entangled product states, which represent the first realization of multi-photon entanglement on a photonic chip [11].

In conclusion, we demonstrate the realization of different optical quantum states by means of integrated optical frequency comb sources. Our results indicate the strong potential to use on-chip frequency combs to generate both heralded single photons and two/multi-photon entangled states.

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