Generation of Complex Quantum States via Integrated Frequency Combs

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***Abstract*— The generation of optical quantum states on an integrated platform will enable low cost and accessible advances for quantum technologies such as secure communications and quantum computation. We demonstrate that integrated quantum frequency combs (based on high-Q microring resonators made from a CMOS- compatible, high refractive-index glass platform) can enable, among others, the generation of heralded single photons, cross-polarized photon pairs, as well as bi- and multi-photon entangled qubit states over a broad frequency comb covering the S, C, L telecommunications band, constituting an important cornerstone for future practical implementations of photonic quantum information processing.**

***Keywords*— Quantum optics; Integrated optics devices; Nonlinear optics, four-wave mixing**

I. Introduction

With the realization of commercial solutions for quantum cryptography, it is foreseeable that reliable, low cost and scalable on-chip sources of single and heralded photons will represent a key enabling technology for quantum communications [1]. The requirements of such sources differ for different applications, but usually include long-term operational stability and insensitivity to environment, compatibility with quantum memories, operation at telecomm wavelengths (around 1550nm) and compatibility with large-scale electronic chip production standards (CMOS). In addition further characteristics such as frequency multiplexing to enable high dimensional multi-user operation or polarization diversity to implement polarization operations are highly desirable to enable versatile applications. Finally, the generation of multiple and large entangled states will open further applications in quantum metrology [2] and computation [3], adding to the large amount of possible applications for versatile and scalable quantum sources. The search for integrated sources has attracted considerable attention [4] from the scientific community, where difficulties arise when sources need to satisfy several requirements at the same time. For example, quantum memories (typically based on atomic transitions) require linewidths on the order of 100MHz. Furthermore, most quantum communication or computation protocols necessitate either pure single photons, or entangled states with high fidelity.

We demonstrate that, by adjusting the pump configuration, integrated quantum frequency combs (based on high-Q microring resonators made from Hydex [5]) can generate pure heralded single photons, cross-polarized photon pairs, as well as multiple entangled photons pairs over a broad frequency comb covering the full S, C and L telecommunication band, with photon frequencies centered at standard telecommunication channels spaced by 200 GHz.

II. Generation of Pure Single Mode Photons

When pump in a self-locked, intra-cavity operation [6], a highly stable integrated source of multiplexed heralded single photons is demonstrated, operating continuously for several weeks with less than 5% fluctuation and without any active stabilization [6]. We performed coincidence measurements for combinations of different signal/idler wavelengths located around the pump wavelength. Clear coincidence peaks are visible on all symmetric channel pairs, while no coincidences are measured between non-diagonal elements of the frequency matrix [6]. For a pump power of 15 mW at the ring input we obtained CAR values between 12.8 and 32.4, and pair generation rates between 14 and 29 Hz per channel (simultaneously). The signal/idler coherence time is determined using time-resolved coincidence measurements, resulting in a measured value of $\Delta\nu$=110 MHz, consistent with the linewidth of the ring resonator (considering the time jitter of the detectors). This narrow linewidth, allowed by the high Q-factor of the microring, makes this device extremely appealing for applications such as quantum memories or quantum repeaters.

III. Generation of Cross-polarized Photon Pairs

By pumping two resonances of orthogonal polarization modes, we introduce a new type of spontaneous four-wave mixing (FWM) to the toolbox of integrated photonics [7]. In particular, we demonstrated the first realization of type-II spontaneous FWM (in analogy of type-II spontaneous parametric down conversion in second order media), which allows to directly generate orthogonally polarized photon pairs on a chip [7]. By properly designing the waveguide dimensions it is possible to tailor the resonances of both polarizations (TE and TM) of the microring resonator in order to generate a frequency offset between the TE and TM modes. In this way they are non-symmetric with respect to the stimulated FWM bands, thus suppressing such process completely. If at the same time the dispersion of TE and TM modes is controlled to achieve similar free spectral ranges, the requirement of energy conservation and phase matching for an efficient spontaneous FWM process can be achieved. When pumped at low power, individual orthogonally polarized photon pairs are generated inside the micro-ring resonator due to type-II spontaneous FWM, which are then separated by a polarizing beam splitter. Using single photon detectors and a time-to-digital converter, a clear photon coincidence peak with a coincidence-to-accidental ratio around 10 at 2mW pump power was measured between orthogonally polarized photon pairs. The clear photon coincidence peak confirms that the FWM process is indeed spontaneous and seeded by the vacuum fluctuations, underlying the fact that the stimulated FWM is successfully suppressed. When the pump power is further increased, the output power increases quadratically until it reaches the optical parametrical oscillation threshold at 14mW, after which the output scales linearly with the pump power [7].

IV. Generation of Entangled Photon Pairs

By changing the pump configuation to excite the resonator with coherent double-pulses, it becomes possible generate time-bin entangled photon pairs [8]. An imbalanced phase-stabilized Michelson interferometer was used to generate them. The double pulses were then coupled into the ring resonator, where their center frequency was matched with a bandpass filter to a single ring resonance. Due to the high field enhancement and high nonlinearity, photon pairs were generated through SFWM on several frequency channels (corresponding to the ring resonances) symmetrically with respect to the pump frequency. To measure the entanglement through quantum interference, we used a second imbalanced stabilized Michelson interferometer with the path length difference matched to the first interferometer. After passing through the second interferometer, we filtered the ring resonance frequencies and measured the arrival times of the photon pairs of 5 channels symmetric to the pump frequency with two single photon detectors [8]. Using time-stamps together with the reference of the pulsed laser (to tag the double pulse) allowed us to post-select the relevant photon events leading to quantum interference (i.e. photons are generated in the first pulse and take the long way in the second interferometer or photons are generated in the second pulse and take the short way in the interferometer, both leading to the same arrival times). For these events, the coincidence rate depends on the interferometer phase, which was adjusted with a piezoactuator-based phase-shifter [8]. By varying the phase of the second interferometer it was possible to measure quantum interference [8]. With a visibility of 83% (without background correction) we obtain a violation of the Clauser-Horne-Shimony-Holt (Bell-like) inequality [9], clearly proving the observation of time-bin entanglement from our integrated photon pair source. The violation of this inequality has been observed in all the 5 channels of frequency pairs symmetric to the pump, thus underlying the simultaneous generation of multiplexed time-bin entangled photon pairs [8].

V. Generation of Multi-photon Entangled States

After confirming the presence of entanglement in the multiple lines, as described above, we performed quantum state tomography and confirmed the generation of qubit entangled Bell states [8]. In order to combine these multiple Bell states to multi-photon entangled states, it is important that all photon pairs are generated from the same excitation field, and that the generated photons have the same bandwidth as the pump field. In this configuration, which is intrinsically given by the resonance characteristic of the ring resonator, the temporal modes of the generated Bell states cannot be distinguished and can thus be combined to multi-photon product states. In particular, we selected four frequency modes, which are symmetric to the excitation frequency, individually forming two Bell states, which are then combined to a four-photon entangled state [8]. We confirm the generation of this four-photon state through four-photon quantum interference, where each photon is passed through an unbalanced interferometer with a path length difference equal to the time-bin separation. Following the post-selection of four-photon coincidences, quantum interference was measured with a visibility of 89% without background correction [8]. We furthermore performed quantum state tomography, where the calculated fidelity of 64%, confirms that the measured density matrix is close to the ideal case.

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