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Pulsed Quantum Frequency Combs from an Actively Mode-Locked Intra-Cavity Generation Scheme

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Abstract: We introduce an intra-cavity actively mode-locked excitation scheme for nonlinear microring resonators that removes the need for external laser excitation in the generation of pulsed two-photon frequency combs. We found a heralded anti-bunching dip of 0.245 and maximum coincidence-to-accidental ratio of 110 for the generated photon pairs.
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1. Introduction

The recently-introduced use of integrated frequency combs (on-chip light sources with a broad spectrum of evenly-spaced frequency modes, generated by optically-exciting nonlinear microcavities) for quantum state generation has provided a solution for scalable and stable multi-mode quantum sources, allowing several frequency modes to be accessible within a single waveguide spatial mode for e.g. multiplexed quantum networks and parallel quantum computing. So-called 'integrated quantum frequency combs' have already been used to demonstrate a variety of multi-channel sources; among these are combs of single photons [1], entangled photons [2,3], qubits and multi-photon states [3]. Pulsed quantum frequency combs –where comb generation does not occur in a continuous operation mode, but rather at discrete time windows, usually with a fixed repetition rate– have particularly attracted recent interest. Specifically, pulsed sources are the basis for time-bin entanglement, an entanglement type very well-suited for current fiber and electronics infrastructures [6], and more importantly, they enable the generation of single-mode photons [4], required for scaling state complexity towards e.g. multi-photon states [3]. Pulsed excitation of nonlinear microcavities also does not suffer from the thermal instability and complexity associated with continuous-wave resonance excitation [5]. However, to date, such schemes have relied on excitation via an external pulsed laser source, not an ideal solution for implementations of quantum sources: the significant bulk and scalability issues of external lasers is incompatible with an approach towards full source integration, while furthermore, the excitation of single microcavity resonances (often having resonance linewidths of ~MHz-order) is energy-inefficient, as most of the laser bandwidth is not used to excite the narrow resonance, and is thus lost.

Here, we demonstrate a new intra-cavity mode-locked excitation scheme and characterize the generated pulsed quantum frequency combs. Specifically, we excite a microring resonator below the optical parametric oscillation threshold using a self-locked cavity configuration. This is the first scheme to generate pulsed integrated quantum frequency combs without the need for an external laser, and combined with its versatility and the integrability of the components used, a step towards a fully on-chip pulsed quantum comb source.

2. Experimental Setup

We constructed a laser cavity (Fig. 1a) around a nonlinear resonant element, featuring narrow bandpass filters to select a single resonance of this resonator, an optical gain component (here an erbium-doped fiber amplifier), and a mode-locking element (an intensity modulator). Our nonlinear resonant element was a 4-port integrated micro-ring resonator with a free spectral range of 200 GHz, and resonances exhibiting Q-factors of 235,000 (~800 MHz resonance bandwidth). By increasing the amplifier gain we achieved lasing on the external cavity modes spanning the selected resonance; a radiofrequency signal corresponding to the cavity repetition frequency (here, 9.75 MHz) or its multiple was then used to drive the modulator and enable the active mode-locking of these external cavity modes to produce a pulse train. The pulses' center frequency was intrinsically-matched to the single ring resonance due to the nested cavity design (a bandpass filter and polarizer were used to assure the excitation of only a single resonance in the transverse-electric mode family). Due to the high field enhancement and high nonlinearity, photon pairs were then generated through spontaneous four-wave mixing (SFWM) on several frequency channels (corresponding to the ring resonances) symmetrically located with respect to the excitation frequency [1]. A high-isolation notch filter then separated the quantum comb from the excitation field, and a frequency filter separated the photon pairs into two spatial modes for the photon detection/coincidence measurements.

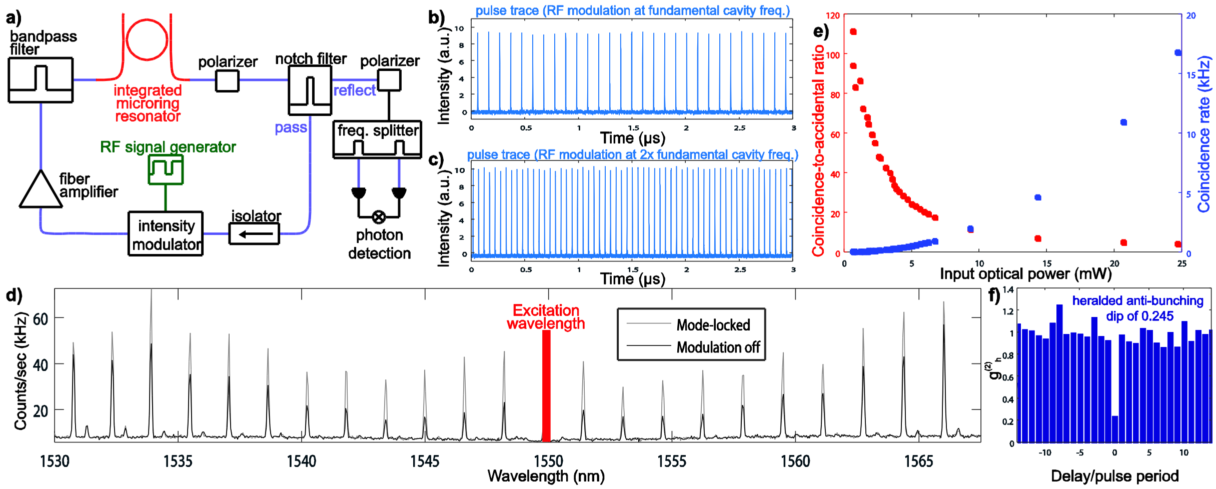

Fig. 1: a) Experimental setup for the actively mode-locked excitation. b) Real-time trace of mode-locked operation with modulation at the fundamental cavity frequency and c) double the fundamental cavity frequency. d) Count spectrum of photons emitted using un-modulated (black) and mode-locked (gray) operation. e) Power dependence of the coincidence-to-accidental ratio and coincidence rate. f) Measurement of the heralded anti-bunching dip, yielding a value of 0.245.

3. Results

By setting the intensity modulation frequency to the fundamental repetition rate of the cavity (determined by the external cavity length), we achieved mode-locked pulsed operation (Fig. 1b). Driving the intensity modulator at multiples of the fundamental repetition rate (upwards of 4x) also resulted in stable mode-locking (Fig. 1c), a significant result as this enables increase of the photon generation rate without sacrificing the pair coincidence-to-accidental ratio (CAR). We measured the output single photon spectrum for both the unmodulated and mode-locked operations at the same optical input power, confirming higher counts and a more efficient excitation using our mode-locked scheme (see Fig. 1d). Finally, we characterized the photon statistics (for the second resonance away from the excitation wavelength) as a function of the average input power into the ring (see Fig. 1e), achieving a maximum CAR of 110 that then decreases with increasing power and increasing coincidence rates. We also used auto-correlation measurements to confirm the purity of the generated state (finding pure single modes, even at multiples of the repetition rate), confirming that the resonance was excited over its entire bandwidth, and obtained a heralded anti-bunching dip of 0.245<0.5 as expected of a source operating in the single-photon regime (see Fig. 1f).

4. Conclusion

Our findings illustrate an entirely novel approach that exploits the resonance pass-band characteristic of the microring resonator to drive a bandwidth-matched (energy-efficient) excitation of the ring and the associated SFWM photon generation process, while preserving the production of high purity photons with high CAR values. Relative to external excitation schemes, our solution allows for a simple and versatile tuning of the comb repetition rate, either electronically by changing the RF modulation signal (which provides an easily-accessible and useful ‘trigger signal’ resource) or by changing the cavity length. As mode-locking was also observed using a potentially-integratable semiconductor optical amplifier rather than the fiber amplifier, this demonstration represents a significant step towards the realization of fully integrated, versatile, and scalable (CMOS-compatible) sources of pulsed two-photon frequency comb states, which are crucial for the development of quantum networks and interconnects, as well as for parallel/multi-channel quantum information processing.

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