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Practical System for the Generation of Pulsed Quantum Frequency Combs

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Abstract: The on-chip generation of large and complex optical quantum states will enable low-cost and accessible advances for quantum technologies, such as secure communications and quantum computation. Integrated frequency combs are on-chip light sources with a broad spectrum of evenly-spaced frequency modes, commonly generated by four-wave mixing in optically-excited nonlinear micro-cavities, whose recent use for quantum state generation has provided a solution for scalable and multi-mode quantum light sources. Pulsed quantum frequency combs are of particular interest, since they allow the generation of single-frequency-mode photons, required for scaling state complexity towards, e.g., multi-photon states, and for quantum information applications. However, generation schemes for such pulsed combs have, to date, relied on micro-cavity excitation via lasers external to the sources, being neither versatile nor power-efficient, and impractical for scalable realizations of quantum technologies. Here, we introduce an actively-modulated, nested-cavity configuration that exploits the resonance pass-band characteristic of the micro-cavity to enable a mode-locked and energy-efficient excitation. We demonstrate that the scheme allows the generation of high-purity photons at large coincidence-to-accidental ratios (CAR). Furthermore, by increasing the repetition rate of the excitation field via harmonic mode-locking (i.e. driving the cavity modulation at harmonics of the fundamental repetition rate), we managed to increase the pair production rates (i.e. source efficiency), while maintaining a high CAR and photon purity. Our approach represents a significant step towards the realization of fully on-chip, stable, and versatile sources of pulsed quantum frequency combs, crucial for the development of accessible quantum technologies.

OCIS codes: (270.0270) Quantum optics; (130.3120) Integrated optics devices; (190.4380) Nonlinear optics, four-wave mixing; (190.4970) Parametric oscillators and amplifiers; (140.4050) Mode-locked lasers.

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1. Introduction

Optical quantum states represent a key resource for quantum information science and have the potential to advance applications beyond proof of concept demonstrations, towards e.g. quantum communications [1], powerful processing and simulations [2], as well as new frontiers in metrology and sensing [3]. The need for a practical quantum technology that enables scalable and mass-producible realizations has led to an increased development of on-chip (integrated) quantum optics platforms, with the ultimate vision of monolithically integrating quantum state generation, processing, and detection elements on the same chip [4,5]. However, while components for integrated photon manipulation and on-chip photon detection still require further development, it must be emphasized that even the efficient generation of large and complex optical states within a small footprint remains a central technological challenge.

The recent demonstration of integrated frequency combs for quantum state generation introduces a possible solution towards addressing this issue [6]. Specifically, these are on-chip light sources with a broad spectrum of evenly-spaced frequency modes, and can be emitted from a nonlinear micro-cavity when one of its resonances is optically excited [7]. When the cavity is operated below the threshold for optical parametric oscillation, two-photon states can be generated: specifically, in third-order nonlinear media, spontaneous four-wave mixing (SFWM) mediates the annihilation of two excitation field photons and in turn the generation of a signal and an idler photon in spectrally-distinct frequency comb modes [8] (Fig. 1). Thanks to the cavity field enhancement, such integrated 'quantum frequency comb' (QFC) sources deliver high quantum state generation rates at low excitation powers compared to plain-waveguide sources (cavities have similarly enhanced pair production rates in, e.g., nonlinear crystal spontaneous parametric down-conversion-based setups [9]). More importantly, this concept also provides a solution for state scalability by allowing several frequency modes (compatible with telecommunications wavelength-division multiplexing channels) to be accessible within a single waveguide spatial mode. Several multi-channel sources based on QFCs have already been demonstrated, among them combs of correlated photons [8], cross-polarized photon pairs [10], entangled photon pairs [11–13], multi-photon states [12], and frequency-bin entangled states [14,15].

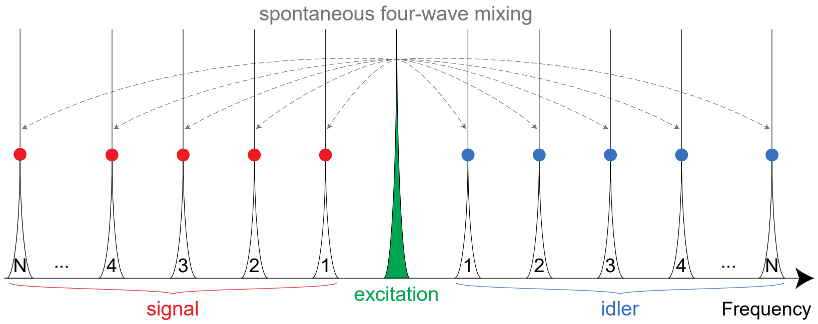


Fig. 1. Operational principle for pulsed quantum frequency comb generation. A pulsed excitation field was coupled to a nonlinear integrated micro-cavity, and through selective frequency filtering, was used to excite a single micro-cavity resonance (green). Spontaneous four-wave mixing mediated the annihilation of two photons from the excitation spectral-mode and the generation of two daughter photons, called signal and idler (red and blue), emitted in spectrally-distinct frequency comb modes. As a consequence of energy conservation, these signal and idler frequency modes had an equal spectral displacement from the excitation frequency (such that the daughter photons occupy, e.g. signal-N and idler-N, where N = 1, 2, 3, 4, 5, etc. is the resonance index).

In contrast to a continuous wave excitation, the pulsed excitation of these QFC micro-cavities –i.e., such that the photon pair generation still occurs probabilistically, but in discrete time windows– is particularly suitable for quantum information applications. Such pulsed sources significantly simplify the synchronization between photon sender and receiver stations, allow for the reduction of detector noise counts through the use of temporal gating or post-selection, and can be used in future systems that feature quantum repeaters or relays where accurate knowledge of photon timing is required for two-photon interference [16]. Additionally, pulsed excitation schemes stand at the basis of time-bin entanglement, a scheme which is very well suited for the existing fiber and electronics infrastructures [17,18]. Moreover, pulsed excitation is necessary for the generation of fully separable two-photon states (i.e., exhibiting no spectral entanglement), enabling the heralding of pure, single frequency-mode photons (by detecting the other photon of the pair) [19]. This is of particular importance as pure single photon states are among the most fundamental entities in quantum optics, and are required for high-visibility multi-source quantum interference (a basis for e.g. linear quantum optical computing) [2] and for scaling state complexity (towards, e.g., multi-photon states) [12].

However, to date, pulsed generation schemes for micro-cavity excitation have relied on lasers external to the source, a far from ideal solution for the realization of efficient and low-footprint quantum light sources. First, such excitation schemes reduce the overall source scalability, and are incompatible with the ultimate vision of a fully on-chip system. Second, the stability of QFC sources relies on the continuous excitation of a micro-cavity resonance, but laser light absorption causes thermal frequency-shifts of the resonance frequencies [20]. For stable long-term operation, this necessitates active compensation of the thermal shift via complex schemes for cavity and/or excitation-wavelength tuning. New methods for micro-cavity excitation without active feedback have been demonstrated [21–23], but lead to chaotic pulse dynamics below the optical parametric threshold, or offer very limited coincidence rates due to multi-stable dynamics at higher pulse powers [24]. Alternatively, pulses with a broad spectral width encompassing the thermal shift range can be used to achieve stable excitation with less complexity; this approach, however, has stricter requirements on the filter isolation and bandwidth necessary to separate the quantum signal from the classical excitation field, and reduces the energy efficiency of the system, in turn increasing the total energy consumption (i.e. most of the laser bandwidth is not used to excite the narrow resonance (100's MHz) and is thus wasted). Finally, external pulsed lasers are largely limited in terms of flexible control of their output, e.g. repetition rate modification, reducing the overall versatility of QFC generation. As pulsed QFCs are among the most promising approaches for on-chip quantum state generation, the resolution of these issues through the development of a scalable, stable, low-power, and versatile pulsed QFC excitation scheme is central to the advancement of sources for quantum information science.

Here, we present a new intra-cavity mode-locked excitation scheme that allows the generation of high-quality pulsed quantum frequency combs in a flexible and efficient manner. Specifically, we excited a nonlinear micro-cavity using a self-locked, nested-cavity configuration with an active modulation and verified the emission of high-purity photon states. This is, to the best of our knowledge, the first scheme to generate pulsed integrated quantum frequency combs without the need for an external laser. Combined with its versatility and the existence of on-chip realizations of the components in the scheme, it constitutes a significant step towards a fully integrated pulsed quantum comb source.

2. Setup

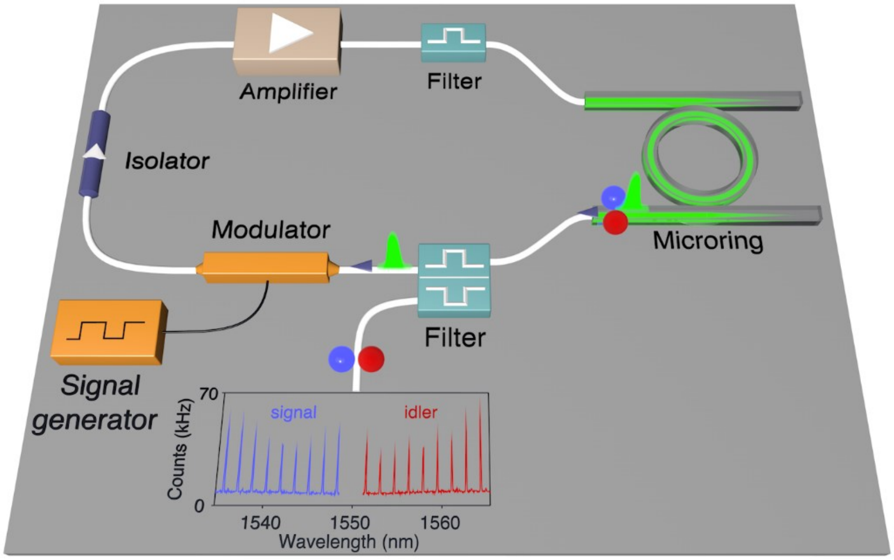


Fig. 2. Experimental setup for the actively mode-locked excitation. The generation scheme for pulsed quantum frequency combs consisted of a nonlinear micro-cavity embedded in a larger, external cavity. The external cavity incorporated an active electro-optic amplitude modulator, an optical gain component, and a narrow band-pass filter, with the latter limiting the scheme's lasing to a pass-band corresponding to a single micro-cavity resonance. The external cavity length was chosen such that several external cavity modes oscillated within the bandwidth of this single resonance. With the introduction of the amplitude-modulation (at a frequency equal to the external mode spacing or a multiple of this quantity), these mode oscillations were phase-locked. This gave rise to a pulsed excitation that was limited to the resonance bandwidth, with a repetition rate corresponding to the modulation frequency. In turn, this pulsed excitation led to the generation of a pulsed quantum frequency comb, which could then be separated from the excitation field via a high-isolation notch filter. *Inset*: Single-photon count spectrum measured after the excitation field was filtered out, acquired using a 12.5 GHz tunable band-pass filter and single photon detector.

Our generation scheme for pulsed QFCs consists of a nonlinear micro-cavity embedded in a longer, external laser cavity (Fig. 2). The external cavity incorporates an active electro-optic amplitude modulator, an optical gain component, and a narrow band-pass filter, with the latter limiting the cavity lasing to a pass-band corresponding to a single micro-cavity resonance. In our particular implementation, the nonlinear micro-cavity was a four-port integrated micro-ring resonator with a free spectral range of 200 GHz and Q-factors of 235,000 (~800 MHz resonance bandwidth) [25]. The amplification element was an erbium-doped fiber amplifier (EDFA), and the mode-locking element was a radio-frequency (RF) signal-driven amplitude modulator. An isolator in the cavity ensured uni-directional pulse propagation, and all components were connected with polarization-maintaining fibers for added environmental stability. The narrow band-pass filter (corresponding to the H34 telecommunications band) limited the cavity lasing to a single micro-ring resonance centered at 1550 nm.

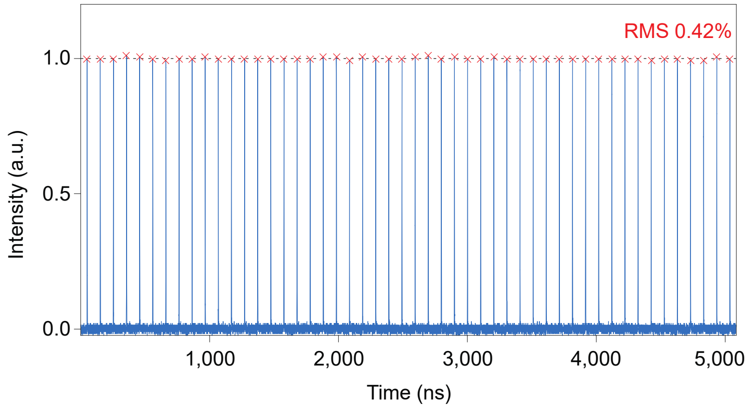
The external cavity length was chosen such that several (approx. 84) external cavity frequency modes oscillated within the 3 dB bandwidth of this single resonance (800 MHz). The relative phases of the cavity modes are usually random, giving rise to chaotic pulsing, but the introduction of the amplitude-modulation (at a frequency equal to the external mode spacing, here 9.8 MHz, or its harmonics), drove these mode oscillations to be phase-locked. This gave rise to a pulse train with a repetition rate corresponding to the modulation frequency, and a bandwidth that is intrinsically matched to that of the micro-cavity resonance, enabling low-power, stable cavity excitation.

3. Characterization

The mode-locked pulsing started immediately once the amplitude-modulation signal was provided via turn-key operation, and enabled a stable pulse train with very low RMS noise (0.42%, Fig. 3(a)) and which, during the course of the output characterization, operated without interruptions for days. While most types of modulation signal can be used for mode-locking (e.g. sine, square, etc.) if they redistribute energy to harmonics of the external cavity mode spacing [26], we specifically made use of a rectangular signal given its ease of implementation. Changing the modulation frequency within ±0.001 MHz of the repetition rate did not affect the mode-locked operation, allowing a range of repetition rate control, and also demonstrating the scheme's overall relaxed driving signal requirements.

By changing the net cavity gain (via the amplifier gain and/or cavity loss), the optical power of the excitation pulse train can be adjusted, which changes the characteristics of the emitted QFC. A high-isolation notch filter was used to separate the excitation field from the QFC for such an evaluation. Signal and idler photons (here, from the second resonance pair away from the excitation field – signal-2, idler-2 in Fig. 1) were routed to separate detectors, where a cross-correlation function ($g_{si}^{(2)}(\tau)$, τ being the signal-idler time delay) of their coincident detections was measured (Fig. 4(a)). The coincidence-to-accidental ratio (CAR) of quantum systems is a key operational metric that compares the probability of obtaining a coincidence detection from photon pairs generated during the same excitation pulse (coincidence rate), with the probability of measuring a coincidence detection event originating between two different excitation pulses, e.g. from dark counts, two different SFWM processes, etc. (accidental rate) [27]. We extracted this ratio from the correlation functions we obtained, and measured the CAR in our system as a function of the peak excitation power coupled into the micro-ring (Fig. 4(b)). The mode-locking operation persisted through the entire power range tested. The system achieved a maximum CAR of 110 and showed the expected CAR decrease with increasing laser powers (caused by a higher probability of generating multiple photon pairs at stronger excitation energies) [27]. The coincidence rate exhibited the predicted increase with growing excitation powers and, at a CAR of 11 (sufficient for, e.g., qubit entanglement verification experiments), we demonstrate coincidence rates of ~1.95 kHz. Taking into account the losses after the micro-ring output (11.4 dB per signal/idler photon), this corresponds to a pair generation rate of ~363 kHz (0.04 pairs per pulse) for this channel couple. We believe that by reducing the losses and using micro-cavities with higher nonlinearity, our scheme can easily be applied to demonstrate even higher coincidence rates. In our resonance-matched excitation scheme, the entire pulse energy can couple to the resonance for excitation, whereas for external lasing schemes (the pulses are typically spectrally-broader than the very narrow resonance), less of the total pulse energy couples into the resonance. For these external schemes, both the CAR and coincidence curves would thus shift towards higher excitation powers (to an extent determined by the ratio of the pulse bandwidth to the resonance bandwidth). This in turn leads to a corresponding drop in the operational power efficiency, which our scheme avoids.

a) pulse trace for modulation freq. equal to the cavity mode spacing



b) pulse trace for modulation freq. equal to 2x the cavity mode spacing

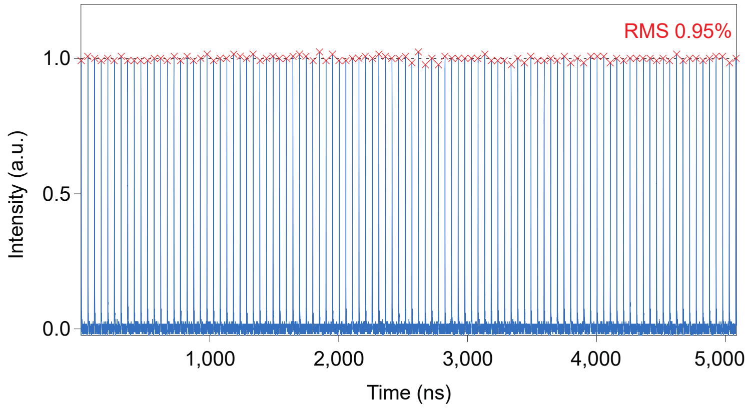


Fig. 3. Laser pulse characterization. (a) Real-time intensity trace of the pulse output, showing 50 pulses with very low 0.42% RMS noise. The trace was captured using a fast detection system (photodiode + oscilloscope with 25 GHz bandwidth). The pulse train corresponds to a mode-locked operation of the setup in Fig. 2, with an amplitude-modulation signal at a frequency corresponding to the external cavity mode spacing (here 9.8 MHz, determined by the external cavity length). (b) Real-time intensity trace, showing 100 pulses with 0.95% RMS noise, recorded when the amplitude-modulation was driven at double the cavity mode spacing frequency, i.e. 19.5 MHz.

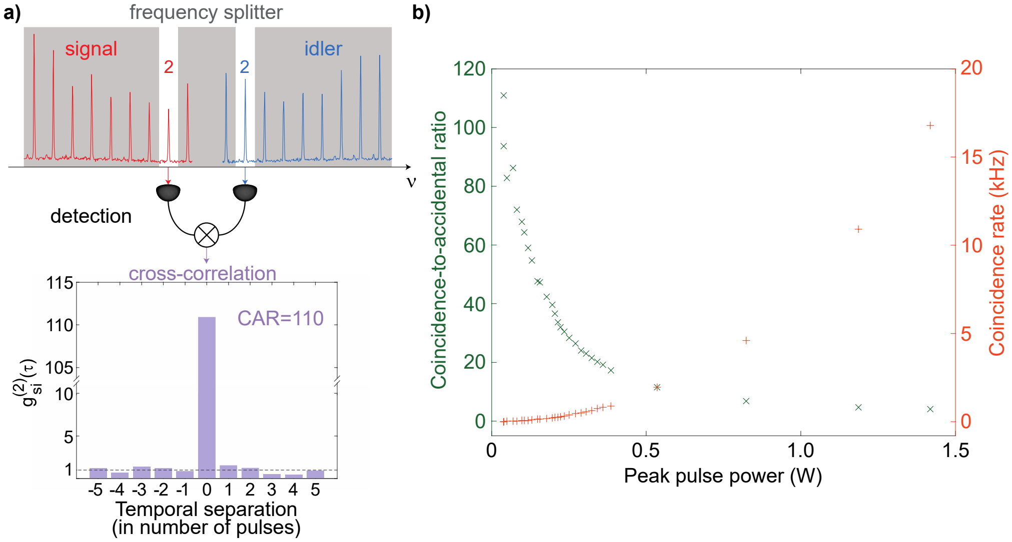


Fig. 4. Characterization of the photon pair coincidence-to-accidental ratio. (a) The signal and idler photons (signal-2, idler-2) were routed to two separate detectors, where a correlation function of their coincident detections was measured. (b). The coincidence-to-accidental ratio showed the expected decrease with increasing laser powers, while the coincidence rate showed the predicted increase, as caused by an increased probability of generating multiple photon pairs at stronger excitation energies.

Finally, a central feature of our scheme is the flexible control of the QFC generation rate. This can be accomplished without changing any components within the cavity, solely by modifying the RF amplitude-modulation signal's frequency. In particular, we observed that by driving the amplitude modulator with frequencies at integer multiples of the external cavity mode spacing, we attained stable harmonic mode-locking at different repetition rates corresponding to the chosen driving frequency (see e.g. Fig. 3(b) with modulation at 19.5 MHz, resulting in a pulse train with 0.95% RMS noise). Interestingly, this repetition rate control enables preserving a high CAR (by maintaining a constant excitation-pulse peak power), while increasing the coincidence rate by using higher pulse repetition rates (Fig. 5, top and middle). As the generation of pure, single frequency-mode photons is central to a variety of quantum information applications, we also verified the emitted photon purity as a function of the system's repetition rate (Fig. 5, bottom). Such a measurement was also of fundamental interest, as at higher repetition rates fewer cavity modes are excited within the resonance, the limiting case of which is single-mode excitation (continuous-wave), commonly associated with multi-frequency-mode daughter photons (i.e., frequency entanglement) [19]. In our measurement specifically, the effective time resolution of our detection system (~100 ps) was sufficient to allow time-domain measurements, thanks to the long nanosecond coherence time of the photons. The output of a single resonance (here, signal-2) was divided by a 50:50 beam-splitter in a Hanburry Brown and Twiss detection configuration [28], with the two outputs used for a second-order coherence function ($g_{ss}^{(2)}(\tau)$) measurement. The maximum of the second-order coherence function was then used to determine the effective number of spectral modes n in the resonance, using the relation $g_{ss}^{(2)}(\tau=0)=1+\frac{1}{n}$ [29,30]. On average, we found an effective mode number of 1.00±0.11 at multiples of the repetition rate, corresponding to a high-purity, separable two-photon state, in turn confirming that the scheme excites the micro-ring resonance over its entire bandwidth [19]. This is a remarkable result with respect to QFC generation, as repetition rate tunability is a central feature that is largely inaccessible when using external excitation lasers. At higher repetition rate harmonics (above the fourth harmonic) we observed increasing pulse power fluctuations, a common challenge for harmonic mode-locked lasers [31]. Future enhancements to the scheme will target stable pulsed operation at even higher multiples of the repetition rate. The implementation of the harmonic-mode-locking advances developed to mitigate instability and supermode noise, including e.g., cavity length modulation [32,33], nonlinear compensation [34], and high-finesse supermode filtering techniques [35,36], could enable access to these higher repetition rate regimes.

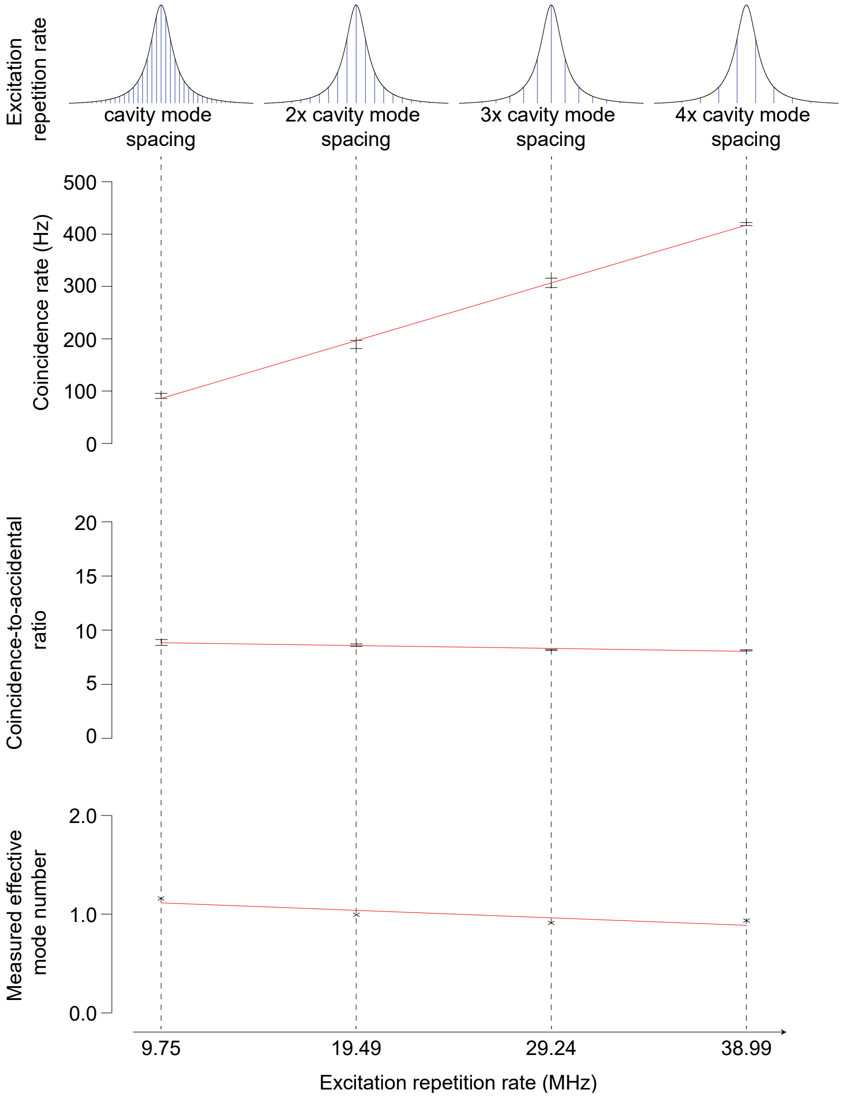


Fig. 5. Characterization of photon emission rate and purity. Top: The coincidence rate was measured for photon pairs produced in the signal-2 and idler-2 resonances as a function of the increasing repetition rate of the pulsed excitation. The coincidence rate was found to grow linearly while the coincidence-to-accidental ratio (Middle) was preserved (as the pulse shape and peak powers were maintained for different repetition rates). Bottom: Second-order coherence function measurements were used to determine the effective number of spectral modes in the signal-2 resonance (see text for details). We found an effective mode number of 1.00±0.11 averaged across the repetition rates tested, corresponding to a pure single-frequency-mode photon state. Red lines (superposed) correspond to linear fit functions.

4. Conclusion

Our findings illustrate a scalable concept that exploits the resonance pass-band characteristic of a micro-cavity to drive a bandwidth-matched (energy-efficient) and stable excitation of the micro-cavity and the associated SFWM photon generation process. When compared to external excitation schemes, our solution allows for a simple and versatile tuning of the repetition rate at which the QFC is emitted, either electronically by changing the RF modulation signal or by changing the external cavity length. In our setup, higher repetition rates were shown to enable increased pair production rates while maintaining photon purity and CAR. Furthermore, as advances to the scheme will enable stable pulsing at higher harmonic mode-locking repetition rates, fewer external frequency modes will be excited within the resonance, leading to new prospects for fundamental studies in the transitory regime between pulsed and continuous wave excitation (e.g. the scaling of photon-pair properties like purity and mode-locking dynamics as a function of fewer excited modes). Future extensions of the scheme, such as the inclusion of supermode noise-suppression techniques [32-36], could potentially also enable the pulse-to-pulse phase coherence required for the realization of a high repetition rate time-bin entangled quantum frequency comb source.

Our approach can be easily applied to a wide range of resonant structures besides third-order nonlinear micro-ring resonators, e.g. photonic crystal waveguides [37] and resonators [38], micro-disks [39], coupled resonator optical waveguides (CROWs) [40], and second-order nonlinear micro-cavities [41]. The bandwidth-matched excitation also gives access to higher-power pumping regimes, useful for, e.g., multi-photon state generation [12]. While we observed mode-locking when the amplitude modulator was replaced with a phase modulator, this was at the cost of a higher sensitivity to the RF driving frequency and the occasional operational instability. We thus used a more robust amplitude-modulated setup, however the scheme can likely make use of phase modulators if coupled with active synchronization methods, e.g. regenerative feedback circuits [42]. Since mode-locking was also observed when the fiber amplifier was replaced by a semiconductor optical amplifier (which can be integrated, like all the other components), this demonstration represents a significant step towards the realization of fully integrated, versatile, and scalable sources of pulsed quantum frequency comb states, crucial for the development of quantum networks and interconnects, as well as for parallel/multi-channel quantum information processing.

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