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InP Membrane Micro-Ring Resonator for Generating Heralded Single Photons

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Abstract: In this paper, we experimentally verify the antibunching properties of multiple single photons located at distinct optical modes in a quantum frequency comb generated by cavity-enhanced spontaneous four-wave mixing in an InP membrane micro-ring resonator. The experimentally measured single photon conditional self-correlation parameter $g_H^{(2)}(0) = 0.08 \pm 0.008$, well below the classical regime (0.5) with the corresponding detector corrected Klyshko efficiency η_k of 3 to 4.2 %.

1. Introduction

Integrated micro-ring resonators for generating quantum frequency combs are attractive sources of single photons which can be used in diverse quantum applications, including quantum communications [1], quantum computing [2], quantum metrology [3] and quantum sensing [4]. Such applications relying on the single photon quantum states have triggered significant interests to explore the various fundamental questions of the entangled states produced in quantum frequency combs. One of the major approaches for single-photon generation by single photon emitter systems, including photons emitted from electronic transition in single atoms, single ions, single molecules, quantum dots, and color centers in various material systems [5]. Alternatively, the generation of single photons is possible by nonlinear processes, including for example heralded correlated pair photon generation using spontaneous parametric down conversion (SPDC) and spontaneous four-wave mixing (SFWM) in χ^2 and χ^3 nonlinear media respectively [5,6]. These approaches are based on a conditional probability where the detection of one photon of the pair heralds the existence of the other photon. Despite the probabilistic nature of these approaches have found applications in the fields of quantum information processing and other quantum applications due to their simplicity and flexibility and can be extended to different nonlinear integrated platforms [7]. Experimental demonstrations of SPDC and SFWM for correlated photon pairs generation have been reported in optical fibers [8,9] and in silicon-on-insulator (SOI) waveguides [10,11], as well as heralded photon-pair generation in III-V photonic crystal waveguides [12,13]. Crystalline semiconductors waveguides, such as silicon, have an advantage over optical fiber-based sources because they only have a very narrow bandwidth of Raman scattering and therefore have no noise from Raman scattered photons outside the Raman bandwidth [14] and they can offer high coincidence to accidental ratios (CAR) which is an important figure-of-merit of any kind of source [15]. Many groups have

already reported correlated photon pair generation in the SOI platform [15-19], using micro-disk and micro-ring resonators, which have several advantages including higher optical density, strong optical nonlinearity, smaller volume to reduce the foot-print and mature fabrication techniques. Such high confinement on an integrated platform enables a very attractive source of single photons. While indium phosphide (InP) based photonic integrated circuits are well established for lasers, modulators, optical switches and receivers with state-of-the-art optoelectronics performance [20]. Despite the fact that InP offers a high nonlinearity than silicon, the low optical confinement and large bend radii in conventional InP platforms hinder their applications for single photon sources. Recent advancements in the InP membrane on silicon (IMOS) platform [21] revealed properties with excellent potential for a single photon source. The high-index contrast of InP membrane waveguides on low-index benzocyclobutene (BCB) buffers enables, high-quality factor and small volume nonlinear micro-ring resonators, as well as monolithic integration with high-performance lasers [22], enabling high potential as the on-chip pump laser for a heralded single photon source. We recently reported an initial study of the use of InP membrane micro-ring resonator for entangled photon generation by SFWM [23]. In that work, we have reported the internal photon generation rate in the InP resonators require ten times lower input power than the silicon. Hence, there may be an advantage in the use of the InP platform for heralded single photons generation because it may have higher generation rate **as reported in Ref. [23]**. In this paper, we experimentally assess the on-chip integrated quantum frequency combs produced in an InP membrane ring resonator, as a heralded single photon source. Our measurements confirm that the heralded single photon detection exhibits conditional self-correlation parameter at $g_H^{(2)}(0) = 0.08$, well below the classical regime (< 0.5) and we detected a photon count rate of 22.7 kHz on the heralding idler channel.

Fig. 1. Experimental Set-up, BPF: Bandpass filter and VOA: variable optical attenuator, PC: Polarization controller (a) Device structure and waveguide Schematic: AWG: arrayed waveguide grating, SNSPDs: Superconducting single photon nanowire single-photon detector and TCSPC: Time-correlated single photon counting, 50:50: fiber beam splitter

2. Results

a. Characterization of device and photon pairs

The experimental set-up is depicted schematically in Fig. 1. The InP waveguide membrane micro-ring resonator is schematically shown in Fig. 1(a): the device is a ring resonator with a radius of 24 μm , side coupled with a single bus waveguide and the gap between ring and bus waveguide is 300 nm. The details on device fabrication and device structure can be found in ref. [21]. The device is optically pumped by continuous-wave (CW) tunable laser to generate quantum frequency comb in this two port micro-ring resonator. The device was mounted on a Peltier cooler to stabilize the resonance from thermal drift caused by the environmental changes during the measurement. Single mode optical fibers were used for in/out coupling in the waveguide via grating couplers which have a loss of about 5 dB per coupler and the center wavelength is measured at around 1490 nm, at which it was optically pumped to excite one of the optical resonance modes for SFWM. The device has low dispersion which enables broadband phase matching for SFWM such that a broad frequency combs of a pure single-mode photons can be emitted at each optical resonance mode. We have shown here up to four distinct resonance wavelength modes in Fig. 2(a) from either side of the pump wavelength due to grating coupler bandwidth limitation. The single photon counts characterization at each resonance wavelength was performed by a high-resolution two-cascaded tunable filter providing more than 120 dB isolation from the pump power in Fig. 2(a). The counts were not symmetrical due to the loss at each channel wavelength and the wavelength dependence of the grating coupler efficiency. The frequency comb spectrum of single photon counts shown in Fig. 2 (a) was obtained from a superconducting Nano-wire single photon detector (SNSPD, from SingleQuantum Eos, SQ059). The dark counts of the detector is < 400 Hz which

was subtracted from the measured single count at each resonance wavelengths in Fig. 2(a). Fig. 2(b) represents the measured resonance linewidth of all accessible resonances within the grating coupler efficiency, and the highest loaded Q-factor was measured to be around 45000 (bandwidth $\sim$ 4 GHz) with 421 GHz free spectral range. The fitting of the measured bandwidth is linear to the wavelength around the zero-waveguide dispersion enables the broadband phase matching condition for SFWM. It is worth mentioning that, the wavelength range was limited due to the grating coupler bandwidth limitation, but it can be further extended with the use of an edge-coupler. In the right side of the plot, the corresponding loaded Q-factor was plotted for each distinct optical resonance mode from Lorentzian fitting as shown in the inset curve.

Fig. 2. (a) Quantum frequency comb generation from a single InP micro-ring resonator measured up to four pairs. The single photons spectrum was measured through high resolution and narrow bandwidth tunable filter. (b) Resonance linewidth over a phase-matching resonance wavelength of an InP membrane resonator. Each point was obtained from Lorentzian fit of the ring resonator shown in the inset curve. The vertical right-side of the plot shows loaded quality factor of the device.

We have measured the quantum frequency comb of four pairs which consist of signal and idler photons from each side of the pump wavelength, with equal frequency detuning as shown in Fig. 2(a). The correlated photon pairs from the cavity-enhanced SFWM in the InP membrane ring resonator is shown up to the first three pairs from the pump wavelength in a histogram mode in Fig. 3(a-c). The coupled power into the waveguide to obtain cross-correlations time-bin histogram was 0.01 mW in Fig. 3(a-c). We chose this power to show the strong correlation between the photon pairs at low gain regime, one can be understood by the highest coincidence to accidental ratio (CAR) in an indium phosphide platform to the date. The CAR value is directly related to the quantum correlation between photon pairs which is an important figure of merit of any kind of correlated photon pair source. Here, all photon pairs (up to three) exhibit very high CARs as shown in Fig. 3 (a-c) at the coupled power of 0.01 mW.

Fig. 3. (a), (b) and (c) Coincidence histogram between first three order of comb lines consecutive to the pump wavelength which have gaussian profile whereas FWHM limited by single photon detector response time and CAR values represent the figure-of-merit of the pairs of photons. The total integration time to obtain the histogram was 5 minutes.

The CAR values were calculated from the number of coincidences at the peak over the number of coincidences away from the peak at a different delay from 0.2 ns to 20 ns. The accidental counts in CAR for the different delays range gave the uncertainty in the value reported here. The measured coincidence histogram width (FWHM) for the three pairs are 99 ps, 95 ps, and 98 ps respectively. The histogram width depends on loaded cavity lifetime of the signal and idler photons and the time jitter of SNSPD. The cavity lifetime of the resonance modes is nearly ~ 36 ps, which was calculated from the Q-factor of the resonance modes and the time jitter of SNSPDs is ~ 35 ps. The FWHM values were consistent with the timing jitter of SNSPDs.

b. Heralding Efficiency

Heralding single photon from a pair of correlated photons is a conditional probability and its efficiency mainly depends on photon extraction efficiency from the cavity. The heralding (Klyshko) efficiency is a measure of a photon reach the detector despite propagation losses. Therefore, Klyshko efficiency at the output of the fiber is represented by [16]:

$$\eta_K = \eta_e T_{\text{tot}} \eta_{\text{det}} \quad (1)$$

where η_e is a photon extraction efficiency which is limited by the distance between the cavity and the single bus waveguide physically defined by the fabrication process, T_{tot} is an overall transmissivity (from the grating coupler, AWG and beam splitter) and η_{det} is a SNSPDs detection efficiency. The overall transmissivity was estimated to be 10.2 % and the detection efficiency is ~ 70 %. Therefore, the Klyshko efficiency is 7.2 % of the photon extraction efficiency in our experimental set-up. The above transmissivity was calculated by the total optical losses (grating coupler and AWG) from the device output to the detector. The detector efficiency is shown above as reported by the manufacturer in their datasheet which could be used with the confidence level > 95 %. So, the maximum Klyshko efficiency could not be achieved more than 7.2 % even if the coupling were optimized in our experimental set-up. The photon extraction efficiency in our set-up is limited by the distance between resonator and waveguide and it's fixed. However, in the experiment, detector corrected heralding efficiency was measured using $N_{13}/(N_3 \cdot \eta_{\text{det}})$, where N_{13} and N_3 are coincidences between signal and idler photons and the number of idler photons [15]. The coincidences between pair of photons were collected within 1 ns time window, measured through time correlated single photon counting (TCSPC) electronics. Therefore, the calculated detector corrected Klyshko efficiency is about ~ 3 - 4.2 % which is mainly limited by the total optical transmission loss at the output of the device and extraction efficiency of the photon from the cavity which is comparable to the reported previously in a silicon ring resonator [15]. The experimentally measured Klyshko efficiency defined as N_{13}/N_3 , independent of the detector efficiency estimates the value of ~ 2.1 - 2.95 %. The detector corrected Klyshko

efficiency value was plotted in Fig. 4(a-c) which is roughly ten times lower than the reported by X. Lu et. al [16]. In their studies, they achieved highest Klyshko efficiency of 46 %, using low loss fiber taper coupling scheme in which the fiber was moved so close to the disk resonator to operate the device in an over-coupled regime to extract most of the incoming photons. However, this approach may not be suitable for the future quantum integrated photonics platform due to its complexity and impracticability. The correlated quantum frequency combs produced by the InP membrane micro-resonator has excellent antibunching properties over the three pairs of comb lines. However, we are not able to measure the self-correlation antibunching properties on the fourth pair in this paper due to the grating coupler bandwidth limitation which significantly reduced the photon coincidence counts probability. Thus, measured coincidence count probability was recorded around zero. All three pairs of correlation measurement showed an antibunching behavior which is much lower than the classical regime (<0.5).

c. Photon Antibunching

The heralding conditional self-correlation measurement was obtained at the zero-time delay between N_1 , N_2 and N_3 using the formula given by [24]:

$$g_H^{(2)}(0) = \frac{N_{123}N_3}{N_{13}N_{23}} \quad (2)$$

Whereas N_{123} , N_3 , N_{13} , and N_{23} are three photon coincidences and idler photon or heralding channel counts, two-photon coincidences between N_{13} and N_{23} respectively [refer to Fig. 1 for labels]. Figure 4(a-c) shows that calculated self-correlation value vs an optical input power, following the quadratic function ($g_H^{(2)}(0) \propto \alpha \times P^2$), where α is a fitted coefficient and P is the coupled power [25]. The value of fitted coefficient was obtained from Fig. 4 (a-b), $\alpha = 24.3 \text{ mW}^{-2}$ and 47.3 mW^{-2} respectively because $g_H^{(2)}(0)$ is proportional to the biphoton rate in SWFM [25]. The lowest calculated self-correlation value is as low as 0.08 ± 0.008 with coupled power $\sim 0.047 \text{ mW}$ at photon count rate of 22.7 kHz on heralding channel from the S_1 - I_1 comb lines, 0.11 ± 0.01 with coupled power $\sim 0.058 \text{ mW}$ at photon count rate of 20.5 kHz on heralding channel from the S_2 - I_2 comb lines and 0.22 ± 0.022 from the S_3 - I_3 pairs shown below respectively.

The error-bars are represented here based on a standard deviation of three experimental data at each point in Fig. 4, which estimates the error of 10 %. The error in the data may result from the false triple coincidences from the leakage of the pump photons or measurement-induced disturbance [26]. The occurrence of false triple coincidences from the leakage of the pump photons is inevitable. But the results of our measurements are shown within the error of 10 %, as their probability is low enough. The leakage of pump photons depends linearly on pump power while the SFWM photon pair scales as the square of the pump power. Therefore, our measurement results as shown in Fig. 4 (a-b), clearly demonstrate the square dependence on the pump power as fitted by the red curve demonstrate the quantumness

measured by the source. There may be some photons scattered by the Raman scattering but it's negligible due to their emission is far away from the measured resonance wavelengths. The external heralding photon count rate was measured directly at $N_3 = 71 \text{ kHz}$ for the S_1 - I_1 , 52 kHz for the S_2 - I_2 and 36 kHz for the S_3 - I_3 at the highest coupled power in the waveguide shown in Fig. 4 (a-c). In Fig. 4(a), we have not measured the data for the coupled power $> 0.09 \text{ mW}$ to show the saturation level of antibunching effect because of the more leakage of the pump photons as they are closer to the pump wavelength and also pump laser wavelength is not stable with the resonance wavelength. The internal heralding rate in the bus-waveguide is much higher, pure, brighter but externally limited here due to the higher total optical loss from the output of our device to the detector.

A comparison with previous work on external heralding rate is tabulated in table 1. Unfortunately, we are not able to collect many points for the S_3 - I_3 correlated pair on heralding efficiency due to the fact that the grating coupler efficiency reduces the coupled power inside the bus waveguide. Hence, at low coupled power inside the waveguide, three photon coincidences, described by the N_{123} coincidence probability in eq. 2 is always zero. Therefore, only two points were measured at higher power as shown in Fig. 4(c). One can obtain more data points by increasing pump power further, but there is a nonlinear blue-shift in the resonances reported here [23]. Also, the probability of multi-photon effects can become dominant at high pump power. Multi-photon effects could add more noise to the experimental data.

Fig. 4. (a), (b) and (c) Self-correlation antibunching properties of single photons to support quantum regime were plotted in the left-hand side and detector corrected Klyshko efficiency was plotted in the right-hand side. Each point was measured at 600 seconds of integration time.

Many groups have studied silicon resonators for SFWM to produce high brightness correlated photon pairs and high entanglement visibility [27-29]. However, the device employed here is a high-Q InP membrane micro-resonator which was previously studied for its spectral brightness and entanglement visibility by SFWM [23] and a comparison with resonators are shown below in table 1.

Table 1. Comparison between Experimentally measured $g_H^2(0)$ and detector corrected Klyshko efficiency η_k

Ref.	Avg. Pump (mW)	Q $\times 10^5$	Heralding rate (MHz)	* $g_H^2(0)$	η_k (%)
[16]	0.073	5	2	0.049	58.9
[15]	0.025	0.92	0.018	0.005	3-4
[30]	1.0	2	3	0.088	
This work	0.047	0.44	0.022	0.08	4.2

*The value reported here as stated in the article.

3. Conclusion

In conclusion, we experimentally demonstrated heralded single photons from quantum frequency combs in an InP membrane micro-ring resonator around zero waveguide dispersion wavelength. The Klyshko efficiency is lower than the fiber-based device reported here [16] but comparable to the silicon ring resonator [15]. The measured conditional self-correlation value is 0.08 ± 0.008 , which is well below the classical threshold (<0.5) and is observed for the first time to the best of our knowledge in the InP membrane platform. The uncertainty in the self-correlation value is may be due to the false triple coincidences arises from the leakage of pump photons and the measurement error. I think we believe our measurement results could be dominated by the noise from the pump photons at the higher power as shown in Fig. 4. This value is higher than the silicon platform because, the noise and losses in our measurement system meant we could not use the same low coupled power as was used in the silicon resonator reported in ref. [15]. Our experimental results could be further improved by the reduction of the total optical loss in the output port to the detector and with an over-coupled micro-ring or a pulley coupled resonator design which may allow us to use a lower pump power and higher Klyshko efficiency.

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