Correlated photon pair generation in low-loss double-stripe silicon nitride waveguides

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Abstract
We demonstrate correlated photon pair generation via spontaneous four-wave mixing in a low-loss double-stripe silicon nitride waveguide with a coincidence-to-accidental ratio over 10. The coincidence-to-accidental ratio is limited by spontaneous Raman scattering, which can be mitigated by cooling in the future. This demonstration suggests that this waveguide structure is a potential platform to develop integrated quantum photonic chips for quantum information processing.

Keywords: quantum optics, integrated optics, silicon nitride, Raman effect

(Some figures may appear in colour only in the online journal)

Introduction
Photonic quantum technology that harnesses the law of quantum mechanics has intrinsic advantages in several applications, such as quantum computation boosted by superposition [1] and quantum communication secured by entanglement [2]. These applications need a scalable and stable photonic quantum system to generate single or entangled photons, process and analyze quantum information. A promising solution is to develop a CMOS compatible integrated platform which has sufficient nonlinearity for photon generation and low loss for linear optical quantum information processing. Silicon has been used to demonstrate on-chip path entanglement [3], in which silicon rings are used for nonlinear photon generation and silicon-nanowire-based linear circuits are integrated for entanglement analysis. However, a propagation loss of 3 dB cm⁻¹ in the silicon nanowire is unacceptable in particular circumstances which require long circuitry, for example, time-bin entanglement circuit contains a few centimeters longer arm in unbalanced Mach–Zehnder interferometers for time-bin generation and entanglement analysis [4].

Compared with silicon, silicon nitride can be made into ultra-low-loss waveguides such as nanowires [5] and double-stripe waveguides [6]. Silicon nitride ring resonators using the nanowire structure have been demonstrated for efficient photon generation, but it is unclear whether the nanowire structure can be made into tens of centimeters long circuits with low loss and high yield for linear optical quantum information processing. The double-stripe silicon nitride waveguides developed by Lionix have a structure of two vertically separated silicon nitride stripes buried in silica. This novel structure offers low propagation loss (0.2 dB cm⁻¹) and tight mode confinement. More importantly, such waveguides can be fabricated using CMOS-compatible technologies at the length of tens of centimeters with high yield [6], which has not been reported in traditional silicon nitride nanowires.

These unique features of the double-stripe silicon nitride waveguide has recently enabled the demonstration of compact linear optical circuits consisting of 50 cm long waveguides for on-chip time-bin entanglement [4]. However that experiment used a nonlinear photon source from a separate silicon chip. If this double-stripe waveguide structure has sufficient nonlinearity for photon generation, both on-chip nonlinear sources and integrated linear circuits could be fabricated on the same chip. The classical nonlinear four-wave mixing (FWM)
in a double-stripe silicon nitride ring resonator has been reported recently [7], implying that such a waveguide structure could be used for photon generation via spontaneous four-wave mixing (SFWM).

In this paper, we demonstrate correlated photon pair generation in the low-loss double-stripe silicon nitride waveguide. We achieve a pair generation rate of 185 kHz and the corresponding coincidence-to-accidental ratio (CAR) is over 10. The result indicates that the low-loss double-stripe silicon nitride waveguide is a potential platform for integrated quantum photonic chips.

Principle and experimental setup

Correlated photon pairs are generated in the low-loss double-stripe silicon nitride waveguide via SFWM. Figure 1(a) describes the principle of SFWM: two pump photons at \( f_{\text{pump}} \) are annihilated to create a signal photon at higher frequency \( f_{\text{signal}} = f_{\text{pump}} + \Delta f \) and an idler photon at lower frequency \( f_{\text{idler}} = f_{\text{pump}} - \Delta f \) simultaneously, where \( \Delta f \) is the frequency detuning between pump and signal (idler). The generated signal and idler photons are referred to time-correlated photon pairs.

Figure 1(b) depicts the cross section of the double-stripe waveguide. Two silicon nitride stripes with a dimension of 170 nm \( \times \) 1200 nm are vertically separated by 500 nm and buried in silica. Figure 1(b) also illustrates the mode profile calculated by a finite-element solver (Comsol 5.1). As we can see, the mode is strongly confined in the silicon nitride stripes. Since silicon nitride has much higher nonlinearity than silica [8], the correlated photon pair is expected to be generated in the silicon nitride stripes. Using the actual length \( L = 6.5 \text{ cm} \), the propagation loss \( \alpha = 0.2 \text{ dB cm}^{-1} \), the group velocity dispersion \( \beta_2 = 750 \text{ ps}^2 \text{ km}^{-1} \) [7] and the nonlinearity coefficient \( \gamma = 0.233 \text{ W}^{-1} \text{ m}^{-1} \) of the waveguide, we obtain the normalized photon flux of double-stripe waveguide through the equation (54) given in [9]. In figure 1(c) the full maximum at half width of the photon flux is around 2.4 THz. To avoid pump leakage (investigated in later text) without sacrificing the efficiency of photon pair generation, the frequency detuning between pump and signal (idler) in our experiments is set to 0.5 THz.

Figure 2 shows the experimental setup. Optical pump pulses at 10 ps width are generated from a 50 MHz mode-locked laser at the central wavelength of 1555.74 nm. The input power is controlled by a tunable attenuator (ATT). Amplified spontaneous emission noise companioned with pump pulses is eliminated by an arrayed waveguide grating (AGW) which has a channel bandwidth of 50 GHz. Since the double-stripe silicon nitride waveguide has polarization-dependent propagation loss and only transmits TE-polarized
light, the waveguide is fiber-pigtained with polarization maintaining fibers at both ends. A polarization controller (PC) adjusts the pump to be TE polarized before entering the double-stripe silicon nitride waveguide. We optimize the polarization by minimizing the polarization dependent loss. The total insertion losses are 4.3 dB including the waveguide-fiber coupling loss (3 dB) and the propagation loss (1.3 dB). The signal and idler photons are separated by an AWG with an insertion loss of 3 dB before being filtered by a tunable band pass filter (BPF). The BPF has an insertion loss of 2 dB and its bandwidth is 100 GHz. Because the superconducting single photon detectors (SSPDs) are polarization sensitive, the polarization of generated photons in each channel is optimized by maximizing the detector counts using a PC with an insertion loss of 1 dB. Once the polarization is optimized, it will be stable as long as we do not touch the fibers and PCs. The detection efficiency of SSPDs is set to 60% and the dark count rate at this efficiency is around 500 Hz. The collection efficiency from the output of the waveguide to the detector in each channel is 10.5 dB. An electronic delay box (DB) in the idler channel is used to shift the coincidence peak to a positive delay in the histogram of coincidence measurement to avoid the loss of coincidence counts. The resolution of time interval analyzer is 27 ps.

Experimental results and discussions

Figure 3(a) shows a typical histogram of coincidence measurements. The main peak located at 48 ns represents coincidences, which record the simultaneous detection of signal and idler photons that are generated from the same pump pulses. It indicates the generation of time correlated photon pairs. The coincidence counts contained in the main peak is described by the raw coincidence rate \((C_{\text{raw}})\). Other smaller side peaks with a time interval of 20 ns records the simultaneous detection of photons from different pump pulses, and the count rate obtained from these side peaks represents the accidental rate \((A)\). The true coincidence rate \(C_{\text{true}} = C_{\text{raw}} - A\) suggests the brightness of a correlated photon pair source, and CAR indicates the strength of photon pair correlations. These two parameters are usually used to characterize the performance of a correlated photon pair source \([10]\).

Figure 3(b) illustrates the dependency of \(C_{\text{true}}\) and CAR on average pump power. The true coincidence rate (diamonds) increases with power, because the efficiency of SFWM scales quadratically with the pump power. The measured true coincidence rate is 1.6 kHz at the pump power of 3.2 mW. Taking into account the collection efficiency, the 1.6 kHz true coincidence rate corresponds to a correlated photon pair generation rate of 185 kHz in the waveguide. CAR (squares) reduced from 16 to 10.6 with the increase of the power due to the generation of multi-pair via SFWM. When the power is less than 3.2 mW, a CAR over 10 is achieved. This suggests the correlated photon pair source can be used for quantum key distribution with 95% error free \([11]\).

We analyze the CAR without other noise except multi-pairs and we find the overall value of CAR in figure 3(b) is far below our expectation. We assume there is only the multi-pair noise and \(\text{CAR} \approx 1/\mu\). Here, \(\mu = C_{\text{true}}/\eta_i\eta_s R\) is average number of photon pairs per pulse, \(\eta_i\) and \(\eta_s\) are the collection efficiencies of idler and signal photons respectively, and \(R\) is the laser repetition rate \([12]\). Using the measured true coincidence rate at the input power of 3.2 mw, we find CAR should be over 270. However, in figure 3(b), CAR is far below this expectation. This significant discrepancy suggests that there are other noise sources contribute to this entire reduction, such as pump leakage and spontaneous Raman scattering (SpRS), which will be discussed in the following paragraphs.

Figure 3. (a) A typical histogram of coincidence measurements at the input average pump power of 3.2 mW. (b) True coincidence rate (diamonds) and CAR (squares) as a function of average pump power; dashed line is a quadratic fit. Error bars are calculated by Poissonian distribution.
We first investigate the pump leakage via coincidence measurements at different pump-idler/signal frequency detunings. The pump leakage results from the spectrum overlap between the pump channel and the selected signal/idler channel. If pump leakage contributes to the majority part of noise photons, the accidental peaks should be similar to the main peak, since the correlation between the detections in signal and idler channel is mainly determined by pump photons rather than correlated photon pairs. The spectrum overlap decreases significantly with the increase of frequency detuning. In figure 4(a), we show the histogram of coincidence measurements with three different frequency detunings at the same average pump power of 3.2 mW. To discriminate the difference between the main peak and the side peaks at each frequency detuning, we intentionally introduce different delays at each frequency detuning via the DB. When the frequency detuning $\Delta f = 400 \text{GHz}$, the accidental peaks are similar to the main peak located at 40 ns. In the case of $\Delta f = 500 \text{GHz}$ (600 GHz), the accidental peaks are quite trivial compared with the main peak, located at 48 ns (52 ns). Note the decrease of the main peak at $\Delta f = 600 \text{GHz}$ compared to $\Delta f = 500 \text{GHz}$ comes from the phase mismatch of SFWM (see figure 1(c)). Therefore, to minimize the pump leakage, we choose a frequency detuning of 500 GHz.

After excluding the first possible noise sources, we attribute the noise photon source to SpRS in the silicon nitride layer. There are two direct ways to confirm this. One is to directly measure the Raman spectrum to show if it overlaps with the frequency range we work at. Previous measurement has shown that silicon nitride has a broadband Raman spectrum that indeed covers the frequency range we work at [13]. The other is to compare the noise level at room temperature and a cooler condition [14] since Raman is temperature dependent. As our waveguide is fabricated on the same chip with other delicate circuits that might be damaged by cooling, we cannot take the risk at this stage to perform this investigation. So we adopt a relatively indirect investigation as explained below.

We analyze the noise contribution of SpRS both in signal and idler channels. Single counts detected by SSPD include photons generated via SFWM and SpRS. The measured single counts include photons generated via both SFWM and SpRS. The photon generation via SFWM scales quadratically with the pump power while SpRS scales quadratically with the pump power. So we adopt a relatively indirect investigation as explained below.

The inferred single counts (C_{i,SpRS}) from SpRS is calculated by $C_{i,\text{SpRS}} = C_{i,\text{total}} - C_{i,\text{SSPD}} - D$.

Here, $C_{i,\text{total}}$ is the total counts detected in idler channels, $C_{i,\text{SFWM}}$ is the single counts generated from SFWM and $D$ represents the dark counts. $C_{i,\text{SFWM}}$ is analyzed by $\mu R$. Figure 4(b) illustrates the inferred results of idler (triangles) as a function of the input pump power. The linear fit (dashed line) indicates that the noise photons are most likely contributed by SpRS, as SpRS is linearly dependent on the pump power. Since only pump pulses propagate in the waveguide and the power is relatively low, it is unlikely to have stimulated Raman scattering.

To further confirm that correlated photon pairs are generated in the 6.5 cm long waveguide rather than in the 6 m long connection silica fibers. We replace the double-stripe silicon nitride waveguide and the pigtailed polarization maintenance fibers by a tunable ATT and two fibers with similar length to repeat the measurement. The total loss of the replacement has been adjusted to 4.3 dB to simulate the waveguide loss. At the same average pump power, the true coincidence rate in silica fibers is less than 4% of the true coincidence rate in the double-stripe silicon nitride waveguide. This confirms that correlated photon pairs are indeed generated in the silicon nitride waveguide.
In the future, we can further improve both the source brightness and CAR. For example, we could design a ring resonator as an ultra-compact nonlinear source component. The enhancement is briefly estimated as follows. Taking the calculated effective mode index (1.72) of the structure and the pump wavelength (1555.74 nm) and using the equation about free spectral range of rings [15]

\[ \text{FSR} = \Delta \lambda = \frac{\lambda^2}{2n_{\text{eff}} r}, \]

we calculate the ring radius \( r \) to be 55 and 111.9 \( \mu \)m for the FSR of 500 and 250 GHz, respectively. We choose these FSR because the frequency detuning between pump and signal/idler in our experiment is 500 GHz and it should be the integral multiple times of FSR. To maintain low losses, the minimum bending radius of the double-stripe silicon nitride waveguide is 70 \( \mu \)m [16]. So a radius of 111.9 \( \mu \)m is a more preferable option than 55 \( \mu \)m. The circumference of the ring resonator is \( L = 2\pi r = 702.7 \mu \)m. The loss per round trip is 0.014 dB. To be realistic, we adopt the \( Q \) factor in [7]: \( Q = 7 \times 10^5 \). Using the known \( Q \) factor, effective mode index \( n_{\text{eff}} \), and circumference \( L \) of the ring, we calculate the finesse \( (F) \) by [15]

\[ F = \frac{Q \lambda}{n_{\text{eff}} L} = 900. \]

As the round trip loss is negligible, the intensity enhancement is

\[ B \approx \frac{F}{\pi} = 286.6. \]

Since SFWM process scales quadratically with the pump intensity while SpRS scales linearly, compared with the straight waveguide pumped at the same intensity, the ring resonator will not only generate photon pairs more efficiently, but will also increase the ratio between SFWM photons and SpRS noise and thus improve the CAR. Furthermore, the required bandwidth of an on-chip filter is not stringent due to the extremely narrow line width of the ring resonator which has already guaranteed the purity of correlated photon pairs. On the other hand, the noise photons from SpRS could be reduced significantly by cooling. More specifically, the Raman noise could be reduced by 70.6\%, using the SpRS equation in [17], if the sample is cooled down to the temperature of liquid nitrogen.

**Conclusion**

In conclusion, we have experimentally demonstrated correlated photon pair generation in a low-loss double-stripe silicon nitride waveguide via SFWM. We have achieved a CAR over 10 when the power is less than 3.2 mW. We find that the CAR is mainly limited by SpRS which could potentially be mitigated by cooling. This work implies that the low-loss double-stripe silicon nitride waveguide is a promising structure for integrating both nonlinear sources and linear circuits in a monolithic photonic chip. It takes us a step further towards integrated quantum photonic chips for various applications.

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