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Photon pair generation in a continuous regime in nanophotonic silicon waveguide

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We report evidence of correlated photon pair generation in silicon waveguides (Si-w) with a continuous wave (CW) pump beam via the degenerated four-photon scattering process. The photon pairs are generated in the spectral region around 1540nm and the correlations between Stokes and Anti-Stokes photons are exhibited by a temporal coincidence measurement using single photon detectors. The peak power of the pump beam in our experiment is two orders of magnitude lower than in previously reported experiments (which used pulsed pump beams). Our results may enable the future realization of fully-integrated quantum optics based on Silicon-On-Insulator (SOI) technology.

Photon pair sources are an important building block for optics based Quantum Information Processing (QIP). For instance, it has been shown that photon pairs can significantly improve the performance of long distance Quantum Key Distribution (QKD), and they are a key ingredient in the Knill, Milburn and Laflamme (KLM) proposal [1] for Quantum Computing with Linear Optics (LOQC). Thus there is a demand for reliable and cheap photon pair sources which must then be combined with reliable and loss-free linear components (interferometers, beam splitters, ...). Integrated interferometers offer high mechanical stability, hence the interest of a recent integrated implementation of the KLM's proposal using Silica-on-Silicon optical circuits [2]. This experiment was realized using photons in the visible range which are easier to detect than photons in the telecom band used for QKD. Nevertheless, recent progress [3, 4] in integrated detection at telecom wavelength suggest that silicon photonics is a reasonable choice for integrated LOQC. Photon pair generation in Si-w benefits from a high intrinsic Kerr nonlinearity and extreme light confinement that enables high optical nonlinearity at low pump power. Early demonstrations of photon pair generation in Si-w have already been reported [6, 7]. These demonstrations used short pulsed lasers to avoid losses due to Free-Carrier-Absorption (FCA). We present here a similar photon pair source in a CW regime. Silicon integrated laser using CMOS-compatible process are easier to implement [4].

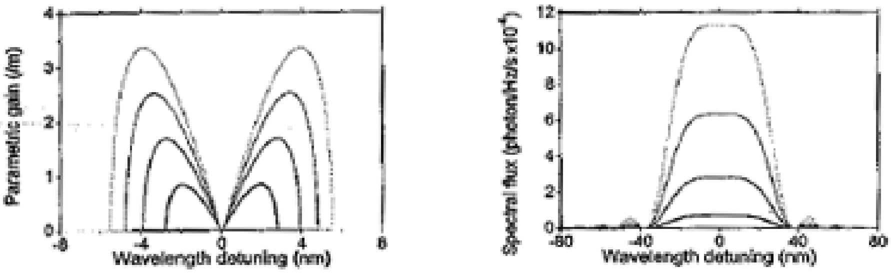

Figure 1: Parametric gain (left panel) and spectral flux (right panel) in Si-w. Pump powers are 3-6-9-12 mW going from black to light gray; effective nonlinearity $\gamma = 280\mathrm{W}^{-1}$; dispersion $\beta_2 = 0.7\mathrm{ps}^2/\mathrm{m}$; length of the si-w is 1cm.

Scalar modulational instability (SMI) which is the process usually used for photon pair generation in Kerr media is nothing more than degenerate four-photon scattering when a phase matching condition is satisfied. Phase matching provides an exponential growth of the generated flux in a restricted spectral range around the pump frequency. As the Kerr nonlinearity in silicon is positive, the phase matching condition can only be satisfied if the group velocity dispersion (GVD) parameter β_2 is anomalous (i.e. $\beta_2 < 0$). The expression of this parametric gain is [8]

$$g(\Delta\omega) = \sqrt{-\left(\frac{\beta_2\,\Delta\omega^2}{2}\right)^2 - \gamma P \beta_2\,\Delta\omega^2} \tag{1}$$

with γ the effective nonlinearity of the waveguide, P the pump power, and $\Delta\omega$ the pulsation detuning with respect to the pump pulsation. The phase matching condition can be easily satisfied in Si-w because the GVD can be readily tuned [10]. In practice, the spectral bandwidth (BW) where phase matching can be obtained is a few nanometers for typical anomalous dispersion of $1\mathrm{ps}^2/\mathrm{m}$ and pump power of a few milliwatt as can be seen in figure1. However, at the low pump power used to generate photon pairs, the spectral range over which photon pairs are generated is considerably wider than the range of real positive parametric gain, see figure 1. Thus from the expression [9] for the photon pair flux generated over a propagation distance z

$$f = \left|\gamma P \frac{\sinh\left[g(\Delta\omega)z\right]}{g(\Delta\omega))}\right|^2 \tag{2}$$

we predict that photon pairs are generated at a rate of 300MHz over a 8 nm bandwidth with 1cm long Si-w and a 6mW pump beam. At this power, nonlinear losses are negligible with respect to the linear scattering losses.

The Si-w we used was fabricated in the ePIXfab at IMEC. Its section is 500nm × 220nm. The in and out coupling is based on integrated grating couplers. Its length is 4.7mm excluding the tapers. The linear propagation loss is estimated to be $4.5 \pm 1.5\mathrm{dB/cm}$. We refer to [5] and references therein for a more detailed presentation of such waveguides. The

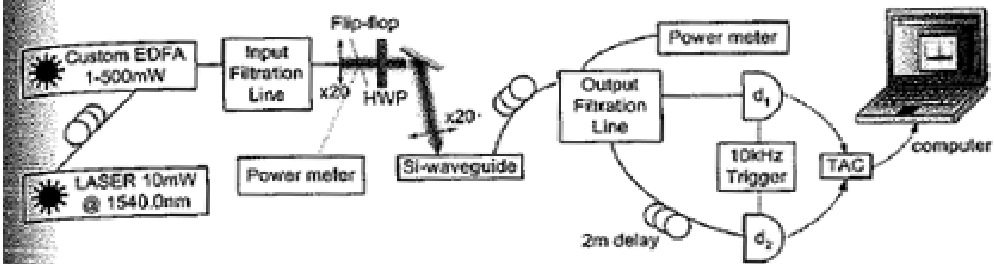

Figure 2: Experimental Setup. The Input Filtration Line play the role of a passband filter. Its specifications are: a −6dB BW = 0.6nm and a −150dB BW smaller than 1.7nm. It is built of two Fiber Bragg Gratings (FBG), two circulators, and three commercial 100GHz Dense Wavelength Division Multiplexer (DWDW) used as passband filters. The Half-Wave Plate (HWP) is used to align the polarization since only the TE-like mode is efficiently coupled inside the Si-w. In order to minimize non linear interactions in the fiber, the light is coupled out of the fiber after the Input Filtration Line and a ×20 microscope objective is used to inject light into the Si-w. The Output Filtration Line is a notch filter with specifications: transmission less than −150dB for 1.7nm BW, transmission around 3.5dB in the range [1542 − 1558]nm for the Stokes port and around 4.5dB in the range [1523 − 1538] for the anti-Stokes port. It is built of one 200GHz DWDM de-multiplexer, two FBG, one isolator, and two commercial Coarse WDM centered at 1531nm and 1550nm. d_1 and d_2 are single photon detectors (model ID−200 from ID quantique) which receive respectively anti-Stokes and Stokes photons. The delay between detection in d_1 and in d_2 is measured thanks to a Time-to-Amplitude Converter (TAC) and data are collected by a computer.

expected flux per unit of spectral frequency in this waveguide is 5×10^{-5}photon/(Hz.s) over a 20 nm bandwidth for a pump power of 5mw. The Output Filtration Line keeps photon pairs over a 15nm bandwidth at both Stokes and anti-Stokes wavelength. Thus the expected photon pair flux is around 95MHz. Photon pair generation is demonstrated with a temporal coincidences measurement: Stokes and anti-Stokes photons are spatially separated and sent into single photon detectors. Distinction between accidental coincidences and coincidences due to correlated photons is obtained by adding a systematic delay on the Stokes photon. The setup of our experiment is depicted in figure 2.

We performed the experiment for different pump power and the best result we obtained in term of signal to noise ratio (SNR) is plotted in figure 3(a) (obtained for 31mW outside the waveguide, corresponding to 5.5 ± 1mW in the waveguide). One can see a peak at the delay corresponding to 2 meters of fiber. Losses between the Si-w and the detectors (due to outcoupling and filtration line) are estimated at 11.5 ± 2dB and 12.5 ± 2dB on Stokes an anti-Stokes photons respectively. Taking into account the 10% efficiency of our detectors, the trigger rate of 10kHz, detection gate width of 50ns, and considering 2ns rescaled time bins (around 11ns delay), we estimate the generated flux in the Si-w to be approximately 15MHz which is around 6 times lower than the expected value. The reason for this discrepancy is unclear. Nevertheless, this rate is in the same range as the previously reported experiment [6, 7]. Another important characteristic is the Signal to Noise Ratio (SNR) defined as the number of coincidences in the real coincidences 2ns time bin divided by the average number of coincidences in the other time bins. For our best result SNR= 3.4 and stays above 2.5 for others pump power. This is in the same range as the value SNR=3.2 which can be deduced[1] from the results presented in ref. [7]

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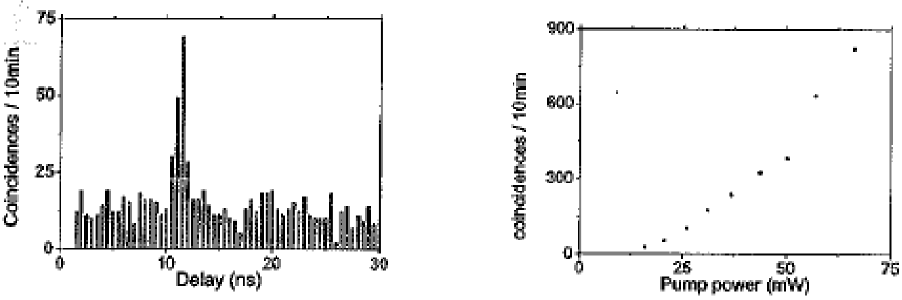
[1] More precisely, in this work detection gate width is 1.4ns and pulse duration 90ps, hense the measured noise in their experiment should be 6.5% of the value in CW operation, leading to the estimate SNR= 3.2.



(a) Histogram of coincidences as a function of the temporal delay between detection of Stokes and anti-Stokes photons. Time bin duration is 0.5ns.

(b) Evolution of the detected photon pair flux as a function of pump power (measured before injection in the Si-w).

Figure 3: Experimental results: demonstration of photon pair generation in Si-w.

In conclusion, we have reported the first demonstration of photon pair generation in Si-w in a CW regime. This suggests the future possibility of full integration of a photon pair source because of availability of both CW lasers and narrow BW filters on SOI platforms. The CW operation may also allow for generation in microring resonators. Finally, we note that it should be possible to significantly improve the SNR ratio by using inverted nanotapers to outcouple the photon pairs.

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