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Correlated Photon Pair Generation in Silicon Wire Waveguides at 1.5 μm *

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Correlated photon pairs at 1.5 μm are generated in a silicon wire waveguide (SWW) with a length of only 1.6 mm. Experimental results show that the single-side count rates on both sides increase quadratically with pump light, indicating that photons are generated from the spontaneous four-wave mixing (SFWM) processes. The quantum correlation property of the generated photons is demonstrated by the ratio between coincident and accidental coincident count rates. The highest ratio measured at room temperature is to be about 19, showing that generated photon pairs have strong quantum correlation property and low noise. What is more, the wavelength correlation property of the coincident count is also measured to demonstrate the correlated photon pair generation. The experimental results demonstrate that SWWs have great potential in on-chip integrated low-noise correlated photon pair sources at 1.5 μm.

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Correlated photon pair sources at 1.5 μm have important applications in quantum information and quantum communication such as quantum key distribution,[1] quantum relay[2] and quantum computing.[3] Traditionally, correlated photon pairs are generated through spontaneous parametric down-conversion (SPDC) processes in crystals.[4] However, the experimental setup is based on bulk optical components, which is difficult to be used in practical quantum information applications due to their large weight and capacity, difficulty in fine optical alignment and limited photon collection efficiency. A modification of this scheme is using period poled waveguides in nonlinear crystal to improve the collection efficiency and to extend the operation wavelength, which has made much progress recently.[5,6] Another promising way to generate correlated photon pairs is through spontaneous four-wave mixing (SFWM) process in fibers, which has been demonstrated experimentally in dispersion-shifted fibers,[7] highly nonlinear fibers[8] and microstructured fibers.[9−12] However, accompanied with correlated photon pair generation, spontaneous Raman scattering (SRS) processes in fibers generate noise photons. To realize practical fiber-based correlated photon pair sources with high quality, methods of SRS noise photons suppression have been demonstrated, such as cooling the fiber by liquid nitrogen[6] or realizing large wavelength spanned correlated photon pair generation in special microstructured fibers.[13]

Recently, SFWM processes in the silicon wire waveguide (SWW) have drawn much attention as a candidate to generate correlated photon pairs.[14−17] SWWs were fabricated on silicon-on-insulator (SOI) platforms, compatible with complementary metal-oxide semiconductor (CMOS) technology. On the one hand, the Kerr nonlinearity coefficient n_2 of silicon is more than 200 times larger than silica. On the other hand, the high index contrast between the silicon core and the silica cladding leads to an extremly small effective area A_{eff} in SWWs. Hence, the nonlinear coefficient $\gamma \propto n_2/A_{\mathrm{eff}}$ of SWW is about 10^5 times larger than silica fibers, leading to an efficient correlated photon pair generation in SWWs with only a few milimeters in length. It is worth noting that due to the crystalline nature of silicon, the SRS florescence spectrum generated in SWWs is a narrow peak with a band width of around 100 GHz and 15.6 THz away from the pump frequency. Hence, high-quality correlated photon pairs can be generated at room temperature by simply selecting the signal and idler frequencies near the pump frequency and far from the SRS peak. In this Letter, 1.5 μm correlated photon pair generation is experimentally demonstrated through SFWM processes in an SWW sample. The SWW used in the experiment is obtained by our own fabrication processes. The experimental results show the great potential of SWWs in realizing on-chip integrated low-noise correlated photon pair sources at 1.5 μm.

The SWW sample is fabricated on an SOI wafer by electron beam (EB) lithography and inductively coupled plasma (ICP) etching. Then a SiO_2 cover layer is deposited by plasma-enhanced chemical vapor deposition (PECVD). The SEM picture of the SWW after ICP etching is shown in the inset of Fig. 1. The silicon core is 500 nm in width and 220 nm in height, re-

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spectively. The calculated γ is around 167.5 $(\mathrm{W{\cdot}m})^{-1}$ for quasi-TE mode. Light is coupled into and out of the SWW by the end-fire method employing two tapered fibers. The tapered fiber has a mode field with the focal length of 4.5 µm and the mode radius of 0.7 µm, respectively. The mode redius is much smaller than the radius of 5 µm for single-mode fibers and is more comparable with the SWW mode. Inverse-taper structures[18] with the tip width of 160 nm are designed at both ends of the SWW to reduce the coupling loss. To avoid the direct coupling between the two tapered fibers, several 180° bends with radius of 10 µm are fabricated along the SWW. The coupling between the tapered fibers and the SWW is realized using a high-precision auto-align system with a resolution of 50 nm. The transmission losses of the SWW are about 2.2 dB/mm, which are obtained by fitting the measured transmission losses of SWWs in different lengths, as shown in Fig. 1.

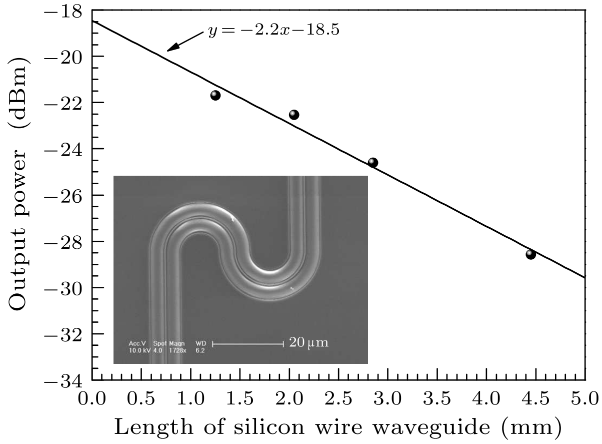

Fig. 1. Transmission loss of the SWW. Inset: the SEM picture of the SWW.

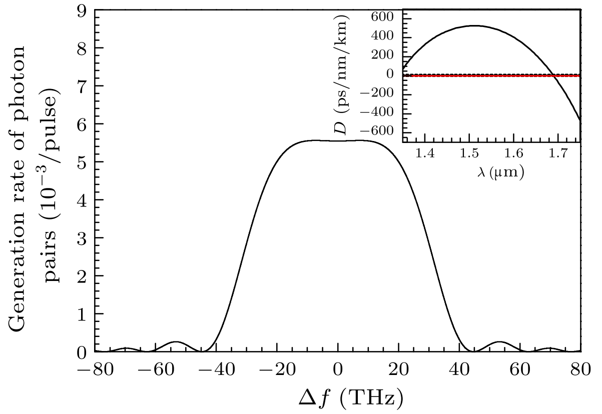

Fig. 2. The spectrum of generated photon pairs under the pump peak power of 100 mW in the SWW. Inset: the group velocity dispersion of the SWW.

The inset in Fig. 2 shows the group velocity dispersion parameter D of the SWW, which has a zero-dispersion wavelength of 1.69 µm. In the experiment the pump wavelength is chosen close to the zero-dispersion wavelength and in the anomalous dispersion area. Using the calculated dispersion and nonlinear property, we analyze the generation rate of photon pairs under the pump power of 100 mW using the theory in Ref. [19], as shown in Fig. 2. We can see that the generation rate is nearly flat when photon pairs are within 20 THz from the pump. This wide-band property of photon-pair generation has been experimentally demonstrated in Ref. [20].

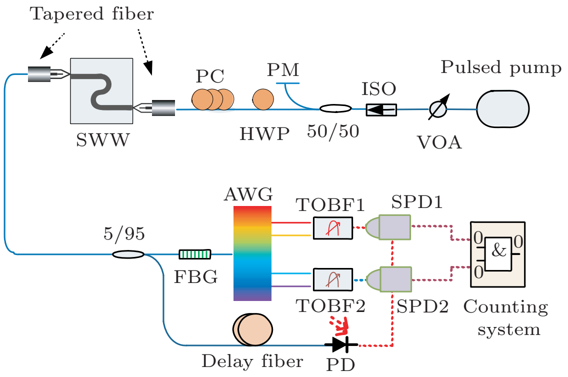

Fig. 3. Experimental setup. VOA, variable optical attenuator; ISO, isolator; HWP, half wavelength plate; PC, polarization controller; PM, power meter; FBG, fiber Bragg grating; AWG, arrayed waveguide grating; TOBF, tunable optical band-pass filter; PD, photon detecter; SPD, single photon detector.

Figure 3 shows the experimental setup for correlated photon pair generation in the SWW sample. The SWW used in the experiment is 1.6 mm in length, with an insertion loss of 13 dB. Its transmission loss and coupling loss of the two ends are estimated to be about 3 dB and 10 dB, respectively. The pulsed pump light is generated by a passive mode locked fiber laser. A filter system based on a fiber Bragg grating, a circulator and a tunable optical band-pass filter (TOBF, Dicon, TF-1550-0.8-9) is used to extend its pulse width by narrowing its spectrum. Then it is amplified by an erbium-dopped fiber amplifier (EDFA). Amplified spontaneous emission of the EDFA is suppressed by a filter system based on two tunable optical band-pass filters, a fiber Bragg grating and a circulator, achieving a side-band rejection of 115 dB at wavelengths as which the signal and idler photon detection is performed. The pulsed pump light has a repetition of 1 MHz, a spectrum width of 0.2 nm and a central wavelength of 1552.79 nm. The duration of the pump pulse is several tens of picosecond, estimated by the linewidth of the pump. The peak pump power coupled into the SWW is several hundreds of milliwatt. A variable optical attenuator (VOA) is used to adjust the pump power. Then a 50/50 coupler is used so that half the pump power can be monitored by a power meter (PM). A rotatable half wavelength plate (HWP) and a polarization controller (PC) are used to control the polarization of the pump light as quasi-TE mode before coupling into the SWW.

Through the SFWM processes in the SWW, two pump photons are annihilated, and a pair of correlated photons is generated simultaneously. The photon with frequency lower than the pump frequency is known as the signal, while the other is called the idler. Energy conservation should be satisfied in the SFWM process, leading to a frequency relation between the pump, signal and idler photons as $2\omega_p = \omega_s + \omega_i$, where ω_p, ω_s and ω_i are frequencies of pump, signal and idler photons, respectively. The generated photon pairs are seperated into two parts by a 5/95 fiber coupler. The photons in the 95% port are directed into two single photon detectors (SPD1 and SPD2, Id Quantique, id201), through a filtering and splitting system based on a fiber Bragg grating, a 100 GHz/40-channels arrayed waveguide grating (AWG, Scion Photonics Inc.), and two tunable optical band-pass filters. Due to the limited bandwidth of the AWG, we cannot measure the whole spectrum of the SFWM processes as the theoretical analysis in Fig. 2. We only choose one pair of channels from the AWG for the experiment. The central wavelength and spectral width of the selected signal photons are 1555.15 nm and 0.37 nm, respectively, while 1550.44 nm and 0.37 nm for idler ones. Total pump suppression is greater than 110 dB for either signal or idler wavelength. The SPDs are working in the gated Geiger mode with a detection window of 2.5 ns triggered by the pump photons from 5% port of the coupler using a photon detector (PD).

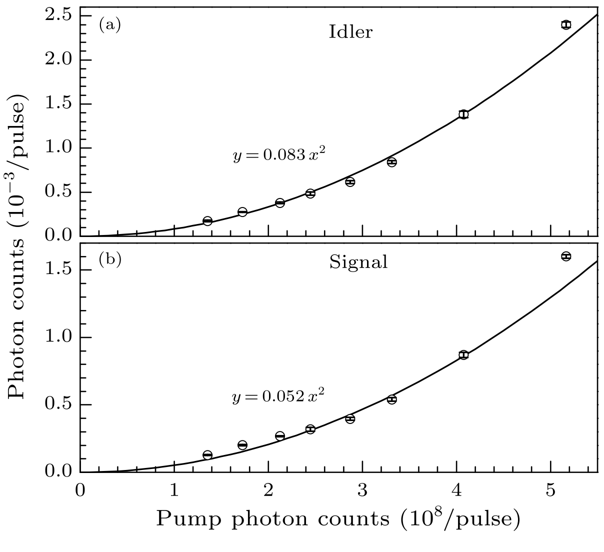

Fig. 4. (a) Idler photon count rate N_i (circle) with increasing pump photon number and its conic fitting curve (solid line). (b) Signal photon count rate N_s (circle) with increasing pump photon number and its conic fitting curve (solid line).

Four photon count rates are measured in the experiment. The single-side photon count rates of the signal and idler photons are denoted by N_s and N_i, respectively. N_{co} denotes the coincident count rate, representing the result that both single photon detectors record photons simultaneously and the detected photons are generated by the same pump pulse. N_{ac} denotes the accidental coincident count rate, representing the result that both single photon detectors record photons simultaneously, but they are generated by different pump pulses. N_{co} and N_{ac} are measured by a counting system with a coincident logic circuit. All the count rates are averaged under a counting time of 180 s.

First, single-side photon count rates are measured under different pump powers, as shown in Figs. 4(a) and 4(b), in which the circles are the experimental result and the solid lines are the fitting curves of experimental data with a conic of N_s, $N_i = aN_p^2$, where N_p is the pump photon number per pulse. The dark counts of SPD1 and SPD2 have been deducted. The single side photon count rates show that the detected photons grow quadratically with the increase of pump power in the experiment, which is the demonstration of the SFWM process. The noise photons are negligible since the selected signal and idler wavelengths are far from the wavelength of the SRS peak, and the pump suppression of the filtering and splitting system is high enough.

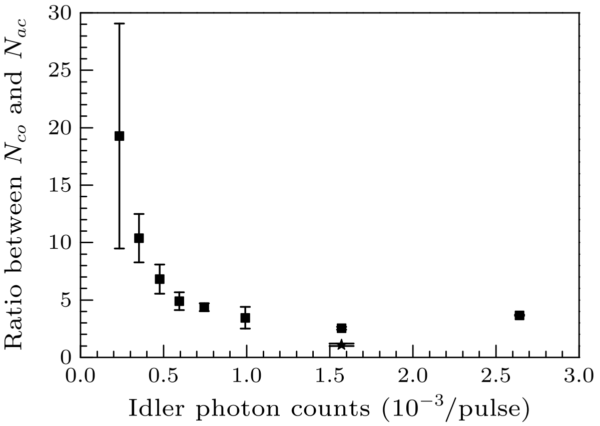

Fig. 5. Ratio between N_{co} and N_{ac} when increasing idler photon count rate. The star shows the ratio between N_{co} and N_{ac} when the SWW is taken away.

To characterize the quantum correlated property of generated signal and idler photons, the ratio between N_{co} and N_{ac} is measured as a function of the idler photon count rate, which is shown in Fig. 5. We can see that the ratio has been greater than 19 under the idler photon count rate of 0.23×10^{-3} per pulse, which can demonstrate the generation of correlated photon pairs. With a further reduce of the coupling loss between the SWW and the tapered fibers, a higher ratio can be achieved. The deviation of the ratio increases with the decrease of the idler photon count rate. This can explain that the total noise photons can compete with the correlated photon pairs under the relatively low photon count rate.

To ensure that photon pairs are generated in the SWW rather than in the transmission fibers, the SWW is taken away, and then the light is directly coupled from one taperd fiber to the other. At the same time, we attenuate the pump power to the same level when the SWW exists. The ratio between N_{co} and N_{ac} is measured when the idler photon count rate is 1.57×10^{-3}/pulse, which is shown by the star in Fig. 5. We can see that the ratio is about 2.53 when the SWW exists in the system. However, the ratio declines to about 1 when the SWW is taken away, indicating a little quantum correlation property. Thus we can conclude that photon pairs are mainly generated in the SWW.

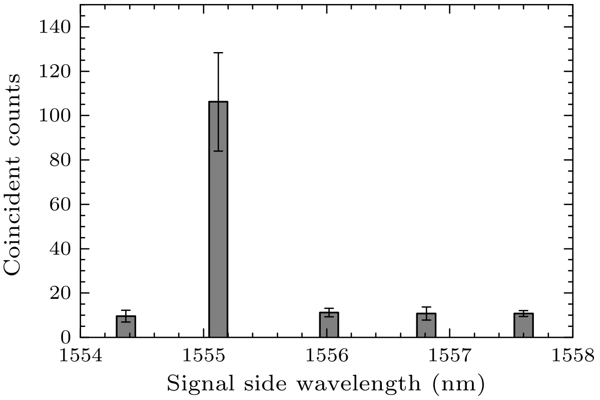

Fig. 6. Coincident counts for 180 s under different signal side wavelengthes when the idler wavelength is fixed.

Finally, to show the correlation property of the generated photons more clearly, coincident counts with different signal side wavelengths are measured under fixed idler wavelength (1550.35 nm) and idler photon count rate, which can be realized easily by selecting different signal channel of the AWG. Figure 6 shows the experimental results. It can be seen that the average N_{co} is 106 for 180 s under the signal wavelength of 1555.15 nm, which is symmetrical with the fixed idler wavelength with respect to the pump wavelength. In contrast, N_{co} is around 10 under other signal side wavelengths. Due to the wide-band property of the photon pairs, 10 coincident counts can be explained because two pairs of photons are generated at the same time. The correlation in wavelength shown by the experimental results further demonstrates the quantum correlated property of the generated photons.

In conclusion, correlated photon pair generation at 1.5 μm is experimentally demonstrated in an SWW with only 1.6 mm in length. The highest measured ratio between N_{co} and N_{ac} is around 19 under room temperature in the experiment, showing its low noise and high quantum correlation property. The quantum correlation property of the generated photons is also demonstrated by their correlation in wavelengths. The experimental results show that the silicon wire waveguide is promising in on-chip integrated low-noise source of correlated photon pairs at 1.5 μm. Further improvement can be achieved by reducing transmission loss of SWWs and coupling loss between fibers and SWWs by optimizing the SWW design and fabrication processes.

References

[1] Gisin N, Ribordy G, Tittel W and Zbinden H 2002 *Rev. Mod. Phys.* **74** 145

[2] Waks E, Zeevi A, and Yamamoto Y 2002 *Phys. Rev.* A **65** 052310

[3] Knill E, Laflamme R and Milburn G J 2001 *Nature* **409** 46

[4] Kwiat P G, Waks E, White A G, Appelbaum I and Eberhard P H 1999 *Phys. Rev.* A **60** R773

[5] Takesue H, Inoue K, Tadanaga O, Nishida Y and Asobe M 2005 *Opt. Lett.* **30** 293

[6] Takesue H and Inoue K 2005 *Opt. Express* **13** 7832

[7] Huang J F, Liu B H, Fang B, Huang Y F and Guo G C 2009 *Chin. Phys. Lett.* **26** 074214

[8] Zhou Q, Zhang W, Cheng J R, Huang Y D and Peng J D 2010 *Opt. Express* **18** 17114

[9] Zhou Q, Zhang W, Cheng J R, Xiao L, Huang Y D and Peng J D 2008 *Proc. SPIE* (China, Hangzhou 27–30 October) 7134

[10] Zhou Q, Zhang W, Zhang S T, Cheng J R, Huang Y D and Peng J D 2009 *Optical Fiber Communication Conference* (California, San Diego 22–26 March) OWD6

[11] Zhou Q, Zhang W, Cheng J R, Huang Y D and Peng J D 2009 *Opt. Lett.* **34** 2706

[12] Zhang W, Zhou Q, Cheng J R, Huang Y D and Peng J D 2010 *Eur. Phys. J.* D **59** 309

[13] Slater J A, Corbeil J S, Virally S, Bussières F, Kudlinski A, Bouwmans G, Lacroix S, Godbout N and Tittel W 2010 *Opt. Lett.* **35** 499

[14] Fukuda H, Yamada K, Shoji T, Takahashi M, Tsuchizawa T, Watanabe T, Takahashi J and Itabashi S 2005 *Opt. Express* **13** 4629

[15] Sharping J E, Lee K F, Foster M A, Turner A C, Schmidt B S, Lipson M, Gaeta A L and Kumar P 2006 *Opt. Express* **14** 12388

[16] Takesue H, Tokura Y, Fukuda H, Tsuchizawa T, Watanabe T, Yamada K and Itabashi S 2007 *Appl. Phys. Lett.* **91** 201108

[17] Clemmen S, Huy K P, Bogaerts W, Baets R G, Emplit P and Massar S 2009 *Opt. Express* **17** 16558

[18] Almeida V R, Panepucci R R and Lipson M 2003 *Opt. Lett.* **28** 1302

[19] Brainis E 2009 *Phys. Rev.* A **79** 023840

[20] Harada K, Takesue H, Fukuda H, Tsuchizawa T, Watanabe T, Yamada K, Tokura Y and Itabashi S 2010 *IEEE J. Sel. Top. Quantum Electron.* **16** 325