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Generation of photon pairs in highly nonlinear photonic crystal fibres for quantum information processing

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Flexible dispersion characteristics and enhanced nonlinearity make the highly nonlinear photonic crystal fibre(PCF) a good candidate to generate photon pairs for quantum information processing. Theoretical background and research progress of photon pairs generated in highly nonlinear PCFs by means of four wave mixing are presented. With a 8.5 m PCF with zero dispersion wavelength near 1552 nm, quantum correlated photon pairs are created around 1550 nm. It may prove eventually feasible to realize efficient, reliable, and low cost photon pair sources for practical applications.

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1. Introduction

Quantum information processing is a new, exciting and rapidly expanding field of interdisciplinary research, whose main goal is to exploit the remarkable properties and phenomena of quantum physics to improve dramatically all aspects of information processing, which is changing the way we view information and physical world. In the last twenty years, we have witnessed a dramatic development of quantum information processing, driven by the prospects of quantum information enhanced communication [1-5], precision metrology [6-10], computation systems [11-15], clock synchronization [16-17] etc. Among available physical systems for practical realizations these novel functions of quantum information processing, photons are the primary candidates for constituting carriers of quantum information. Efficient generation and transmission of quantum-correlated or -entangled photon pairs play important roles in practical engineering applications. Over the past ten years, various attempts have been made to develop efficient photon pair sources, and most of them are based on spontaneous parametric down-conversion (SPDC) in second-order [$\chi^{(2)}$] nonlinear crystals[18-25], such as beta barium borate, periodically poled lithium niobate, $LiIO_3$, $KNbO_3$, and quasi-phase-matched $KTiOPO_4$ etc. A pump photon (ω_p) annihilates and generates a pair of twin photons: signal (ω_s) and idler(ω_i), where $\omega_p = \omega_s + \omega_i$. It should be noted that photon pairs around 1532 were also achieved, in which the effective $\chi^{(2)}$ of periodically poled silica fibres was used [26]. The process of SPDC is subject to conservation of Energy and momentum. The latter is also called phase matching condition. Phase matching can be achieved in birefringent crystals if either both, or one of the down-converted photons are polarized orthogonally with respect to the pump photons. The first type is referred to as type I phase matching, and the second type as type II phase matching. If the birefringence of the crystal can not be exploited, it is possible to achieve so called quasi phase matching in crystal where the sign of the $\chi^{(2)}$ nonlinear coefficient is periodically reversed. Though great progress has made using this method, crystal waveguides generally offer a relatively shorter interaction length and this photon pair creation process is inefficient. In addition, it is important to couple the photon pairs into standard optical fibres for transmission, storage, and manipulation over a distance for applications, but photon pairs based on SPDC in nonlinear crystals suffer from loss and mode matching problems when coupling to optical fibre[27-28]. Therefore, there has been a growing interest in direct generation of photon pairs in optical fibre recently. Another advantage of fibre-based photon pair sources over those based on SPDC in nonlinear crystals is that the spatial mode of photon pair would be the guided transverse mode of the fibre[29-31], like a very pure Gaussian single spatial mode in optical fibre, so it is possible to multiplex several quantum channel on existing fibre plant. In fact, entangled and correlated photon pairs generated in optical fibres have been proposed [32-37]. Generally speaking, it will take several hundred meters or kilometers to create photon pairs via nonlinear effects in the conventional optical fibre.

The advent of new materials, nano-technology and nano-manipulation have allowed quantum phenomena to extend to a wider range, which provides more possibility of applications of quantum effects and breathes life into quantum information processing[37-41]. Photonic band gap structures offer the ability to design new optical properties in existing materials by wavelength scale periodic microstructuring the material configuration. The photonic crystal fibre (PCF, also called microstructured fibre and holey fibre) is a silica optical fibre with an ordered array of microscopic air holes running along its length. Unlike the conventional fibre, the guidance properties of the PCF are determined by the size, pattern of air holes and the solid-silica regions rather than by the properties of optical glass. Light is guided through small solid core PCFs, where high intensities can be maintained for interaction lengths of several meters resulting in large nonlinear effects. In addition, PCFs allow a more flexible tailoring of the dispersion properties, which are crucial for many applications. Recently, we have discussed technical reasons behind great research interest of highly nonlinear PCFs in optical communication components[41]. Here we will discuss and review generation of photon pairs in highly nonlinear PCFs via FWM. The wavelengths of photon pairs achieved in mostly reported experiments are away from low loss window of the fibre. In theory, highly nonlinear PCFs can be used to generate photon pairs at any desired wavelength[42]. Experimental results of generation of correlated photon pairs around 1550 nm in a PCF of 8.5 m are presented, which is expected for transmission in optical fibres.

2. Theoretical background

FWM in the optical fibre is a scattering process, which has long been studied. A simplified energy diagram with four beams coupling three virtual excited state $|a\rangle$, $|b\rangle$ and $|e\rangle$, and a ground state $|g\rangle$ is shown in Fig.1[36]. Two pump photons at frequency ω_p are absorbed, a pair of signal ω_s and idler photons ω_i are created. For efficient interaction, the following phase matching and conservation of energy should be met,

$$2k_p - k_i - k_s + 2\gamma P_p \approx 2\gamma P_p + \beta(\omega_s - \omega_p)^2 = 0 \quad (1)$$

and

$$\omega_s + \omega_i = \omega_p \quad (2)$$

where $k_{s,i,p}$ are the wavevectors of the signal, idler and pump photons, β is the group velocity dispersion (GVD) coefficient; P_p is the peak pump power and γ is the nonlinear coefficient of the fibre,

$$\gamma = \frac{2\pi n_2}{\lambda_p A_{eff}} \quad (3)$$

where n_2 is the nonlinear refractive index of fibre core, A_{eff} is the effective area of the fibre core mode and λ_p is the pump wavelength. The primary factors influencing FWM process in the fibre are : the nonlinear coefficient γ, the pump power P_p, the fibre length L, and the GVD β. By operating near the zero-dispersion wavelength and considering dispersion, phase matching condition can be met. With a well-designed highly nonlinear PCF, efficient FWM can be achieved at any desired wavelength with a short fibre and relative low pump power[41].

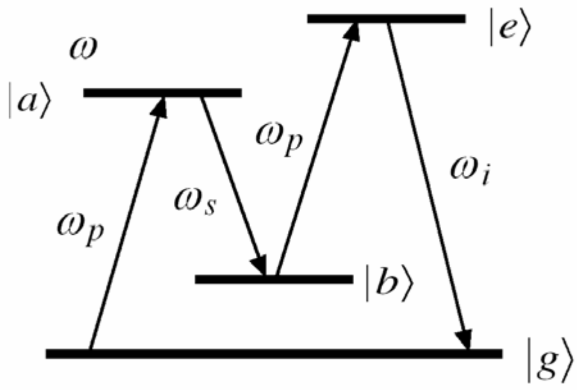


Fig.1 Schematic energy diagram for photon pairs generation via FWM

Quantum theory of twin photon generation via FWM in optical fibres has been discussed in detail[29, 36], and the coincidence rate C_r of signal-idler photon pairs with pump power, nonlinear coefficient and fibre length follows

$$C_r \propto (\gamma P_p L)^2 \quad (4)$$

From the above equation, we can see that the coincidence rate scales quadratically with pump peak power. This is a distinct feature of FWM of the $\chi^{(3)}$ interaction, compared with the linear dependence on pump power in $\chi^{(2)}$ SPDC.

3. Experimental demonstrations

Recently, PCFs with high nonlinearity and relatively low loss have become possible to manufacture, which opens up possibilities for many new applications. Several research groups have carried out experimental investigations of generation of photon pairs in highly nonlinear PCF of several meters, which shows the huge potential of applications of the PCF to generation of photon pairs. In addition to reviewing the state of the art status of research, an experimental result of generation of photon pairs around 1550 nm is presented.

3.1 Generation of correlated photon pairs via spontaneous FWM

High brightness sources of photon pairs are required in various applications of quantum information processing. Pumped a PCF in the normal dispersion regime, the sidebands generated are widely spaced at equal frequency intervals from the pump, and a high brightness photon pair source can be achieved as shown in Fig.2(a)[43]. A mode-locked picosecond Ti:Sapphire pump laser is sent onto a prism P to remove in-band light from the pump laser spontaneous emission. The pin hole is used to improve the pump mode and the attenuators to reduce the power down. A half wave-pate(HWP) is used to align the pump polarization along one axis and prevent polarization scrambling. The output of the 2 m PCF with zero dispersion wavelength at 715 nm is collimated using an aspheric lens, followed by a removable mirror M, allowing to monitor the photon pair spectra to launch them into a coincidence test bench. A dichroic mirror spreads the incoming beam into two arms, one corresponding to the signal and the other to the idler. Two band-pass filters F1 and F2 centered at 570 and 880 respectively are used to remove in-line pump and background. The detected photons by two silicon avalanche photodiodes(APD) are counted in a dual-channel counter and the coincidences are analyzed by a time interval analysis system(TIA).With the pump laser operating at 708.4 nm, correlated photon pairs at 587 nm and 897 nm are created simultaneously. The coincidence rate as a function of pump is plotted in Fig.2(b), from which we can see that up to 3.2×10^5 net coincidences per second can be achieved. Another experiment is carried out by this research group with PCFs with zero dispersion wavelength close to 1060 nm and a nanosecond Q-switched laser of 1047 nm as pump laser[44]. With the PCF of 6 m long, pair photon rates up to 6.7×10^6 s^{-1} are generated at 839 nm and 1392 nm respectively.

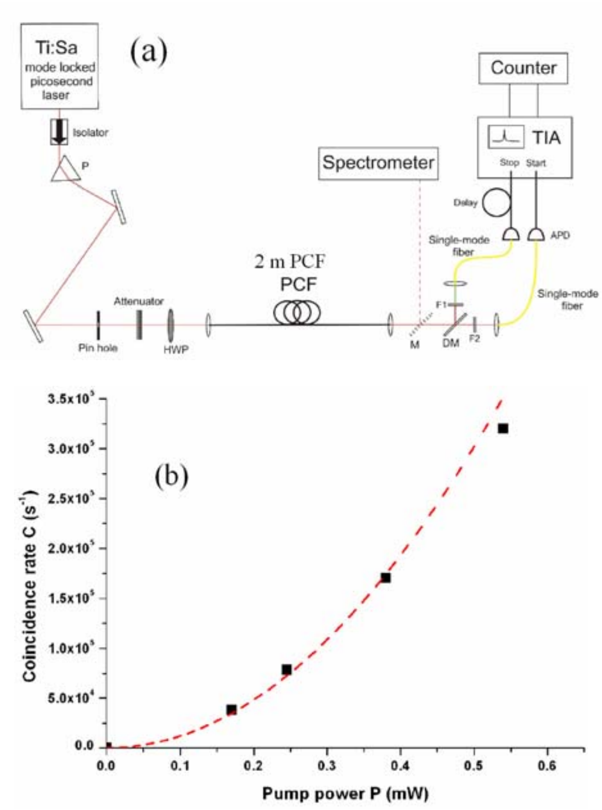


Fig.2. (a) Optical layout of experimental setup. (b) Net coincidence rate versus the pump power.

A experimental setup on measurements of correlations in the photon pairs generated in a birefringence PCF is depicted in Fig.3(a)[45]. Linearly polarized, picosecond pump pulses are launched into a 5.8 m PCF such that the plane of polarization is aligned along one the polarization mode axes of the fibre. The resulting signal and idler photon pairs co-propagate along with the pump and emerge from the PCF. The output of the PCF consists of a number of pump photons that are separated in wavelength from the pump by about 10 nm. For efficient detection of the signal-idler photon pairs, pump-photon is suppressed by three diffraction gratings so that two different spectral regions can be detected on two photon-counting modules(PCMs). Proper choosing the pump, signal and idler wavelengths, and careful alignment of the system are important to obtain the desired result, as shown in Fig.3(b). The choice of pump respect to the fibre's zero dispersion wavelengths influences dramatically the signal-idler photon pair production rate. The PCF's zero dispersion wavelength is polarization dependent due to birefringence in the PCF, which means that polarization of the pump also affects the signal/idler count rate. Fig.3(c) shows a plot of coincident counts as a function of the number of pump photons per pulse.

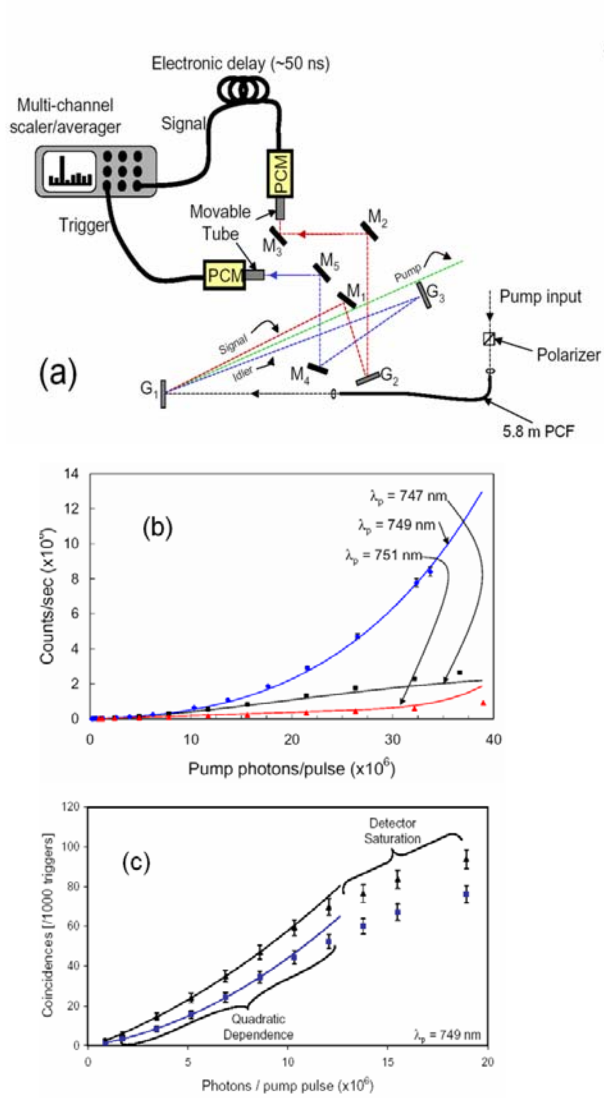
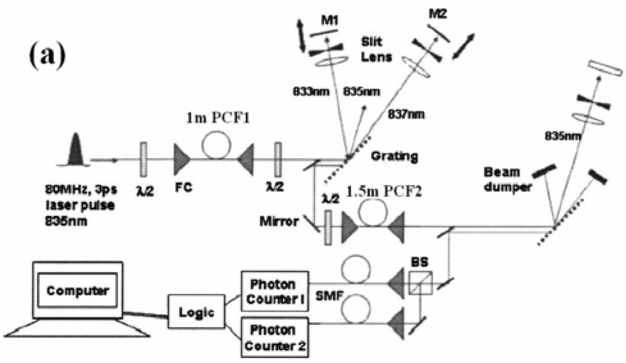


Fig. 3. (a) Experimental setup used to generate and detect photon pairs. (b) The idler count rate with three different pump wavelengths. (c) Total coincidence counts(triangles) and accidental coincidence counts(boxes) versus the number of pump photons per pulse.

3.2 Generation of correlated photon pairs via a reversed degenerate FWM process

In the reversed process of the degenerate FWM process, a pair of signal ω_s and idler ω_i photons can be annihilated to create two pump photons ω_p of the same color, $2\omega_p= \omega_s +\omega_i$. Two new photons are generated simultaneously and hence are correlated[46]. The experimental setup is shown in Fig.4(a). A Ti:sapphire laser emitting pulses of 3 ps at 835 nm drives the FWM process in a 1 m PCF1. The output of PCF1 is collimated onto a diffraction grating. With two narrow slits, a pair of signal at 837 nm and idler at 833 nm light is selected. By using two movable mirrors M1 and M2, the relative timing between the signal and idler pulses can be adjusted. The linearly polarized signal and idler pulses are adjusted to the same principal axis of PCF2 and coupled to it. The output photons are selected with another grating and filtered with a narrow slit, and only those photons at the wavelength of 834.8 nm are directed to a 50/50 nonpolarizing beam splitter. The output beams from the beam splitter are coupled into two single-mode fibres and are detected by two photon counters. Photonelectronic pulses are analyzed by gated logical units for coincidence measurements. The experimental measured coincidence counting rate as a function of peak pump power is plotted in Fig.4(b) with filled circles. The theoretical values are also shown with the solid curve.



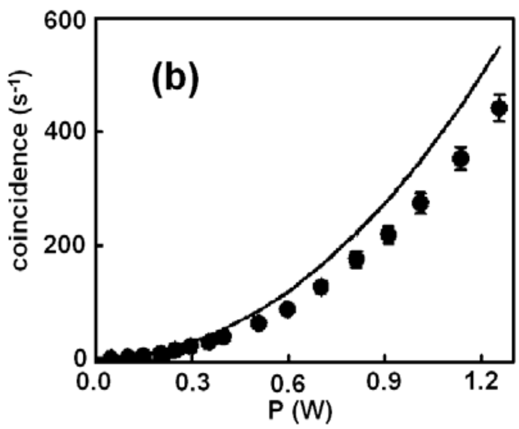


Fig.4 (a) Schematic experimental setup via reversed degenerate FWM. (b) Coincidence rate versus peak pump power P.

With a similar experiment setup performed in the above, the generation of cross-polarized photon pairs with cross-polarized frequency-conjugate laser pump pulses are proposed and experimental demonstrated[47]. Experimental result shows that the contrast ration between coincidence count rate and accident coincidence count rate in cross-polarized pump scheme is lower than that in the above scheme.

3.3 Generation of correlated photon pairs around 1550 nm

To distribute photon pairs in standard fibre efficiently, it is important to create them in fibre's low loss window. The experimental setup is shown in Fig.5(a).The light with a wavelength of 1552 nm form an external cavity semiconductor is modulated into 90 ps pulses by an intensity modulator(IM). The modulated pulses are amplified by two EDFAs, with two tunable filters(TFs) to reduce the amplified spontaneous emission from EDFAs. The pulses are then input into a 8.5 m high nonlinear PCF with zero dispersion wavelength near 1552 nm after polarization controller(PC). In the PCF, correlated photon pairs are generated through spontaneous degenerate FWM process. The pump power can be adjusted by changing the pump current of two EDFAs. The measured output spectrum form the PCF on the optical spectrum analyzer with pump power of 80 mW is shown in Fig.5(b). We can see that the signal and idler in the spectrum are almost symmetrically distributed beside the pump light.

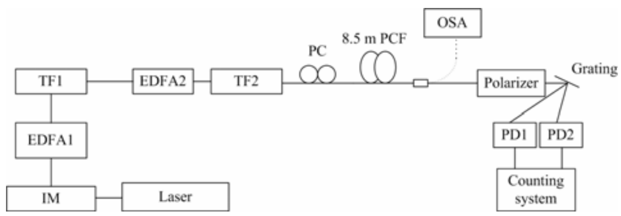


Fig.5(a) Experimental setup to generate photon pairs around 1550 nm

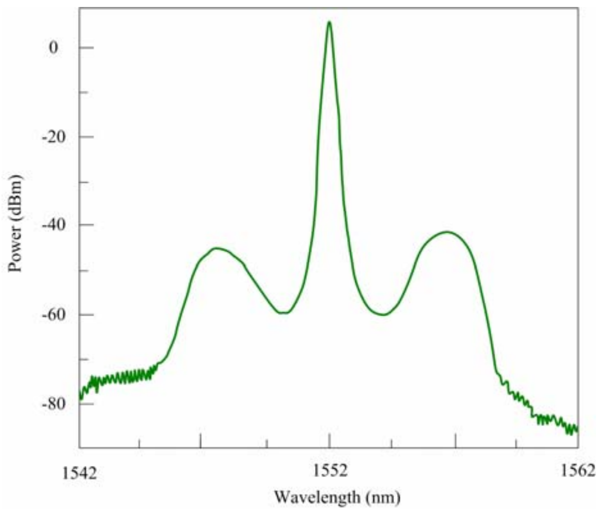


Fig.5(b) Spectrum from the PCF with pump power of 80 mW.

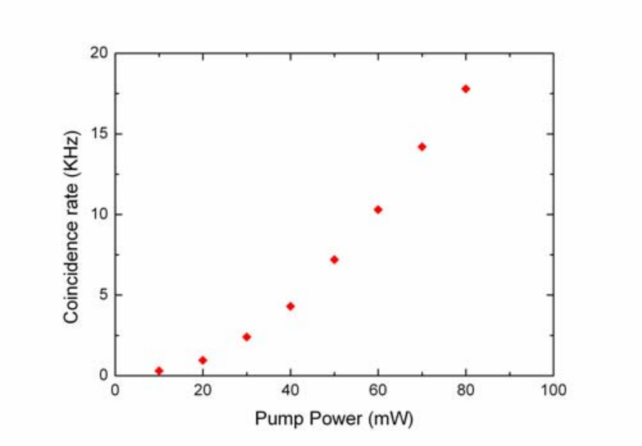


Fig.5(c) Coincidence rate versus pump power

A diffraction grating is used to spatially separate the signal the pump and the idler photons. The doubly diffracted signal and idler photon are then recoupled into two photodiodes(PD) to count photons in the counting system. The experimentally measured coincidence counting rate as a function of pump power is given in Fig.5(c), which shows the coincidence rate increases with the square of the pump power.

4. Conclusion

Generation of correlated photon pairs have been demonstrated experimentally via FWM in highly nonlinear PCFs of several meters with different configurations. With a 8.5 m PCF with zero dispersion wavelength near 1552 nm, quantum correlated photon pairs are created around 1550 nm. Most of the work is currently motivated by the potential applications to quantum information processing. The short device length will enhance system stability and reliability. Although the present experimental results need further improvement, they are nonetheless promising for quantum information processing. It may prove eventually feasible to realize efficient, reliable, and low cost photon pair sources for practical applications.

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