

Polarization entanglement generation at 1.5 μm based on walk-off effect due to fiber birefringence

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In this Letter, a linear scheme to generate polarization entanglement at 1.5 μm based on commercial polarization maintained dispersion shifted fiber (PM-DSF) is proposed. The birefringent walk-off effect of the pulsed pump light in the PM-DSF provides an effective way to suppress the vector scattering processes of spontaneous four-wave mixing. A 90 deg offset of fiber polarization axes is introduced at the midpoint of the fiber to realize the quantum superposition of the two correlated photon states generated by the two scalar processes on different fiber polarization axes, leading to polarization entanglement generation. Experiments of the indistinguishable property on single-side and two-photon interference in two nonorthogonal polarization bases are demonstrated. A two-photon interference fringe visibility of $89 \pm 3\%$ is achieved without subtracting the background counts, demonstrating its great potential in developing highly a efficient and stable fiber based polarization-entangled quantum light source at the optical communication band. © 2012 Optical Society of America

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Polarization entangled photon pair source at 1.5 μm has important applications in quantum communication [1–3] and quantum information processing [4]. In recent years, spontaneous four-wave mixing (SFWM) process in optical fiber has received much attention as an important way to realize all-fiber quantum light source. When pulsed pump light passes through a piece of optical fiber, two kinds of SFWM processes take place simultaneously [5]. One is the scalar scattering process, in which the two annihilated pump photons and the generated photon pairs are all polarized along the same fiber polarization axis. The other is the vector scattering process, in which the two annihilated pump photons are polarized along different fiber polarization axes, as are the generated photon pairs. For fibers without birefringence, such as dispersion shifted fibers (DSFs) employed in most previous experiments, the two processes are indistinguishable. The generated photon pairs always have the same polarization state with the pump light. To realize polarization entanglement, sophisticated schemes, such as time-multiplexing [6,7] and the polarization diversity loop [8,9], have been demonstrated to generate two orthogonally polarized correlated photon states and make them in quantum superposition in space and time.

Recently, utilizing the difference between the phase-matching conditions of the scalar and the vector scattering processes in a piece of microstructured fiber (MSF) with group birefringence, we have realized polarization entangled photon pair generation employing a simple linear scheme [10]. These results demonstrate that the fiber birefringence could provide a much easier way to generate polarization entangled photon pairs. However, due to the lack of uniformity in performance, high splicing loss and high cost of the MSF, the potential on real application of the MSF based scheme is limited.

In this Letter, we propose and demonstrate a new scheme for polarization entangled photon pair generation based on polarization maintained DSF (PM-DSF). When linearly polarized pulsed pump light is injected into

a piece of PM-DSF with a polarization direction of 45 deg with respect to the fiber polarization axes, the two pump components polarized along the two polarization axes will walk off rapidly due to the high birefringence of the PM-DSF as shown in Fig. 1(a), resulting in an effective suppression of the vector scattering processes. Hence, correlated photon pairs are mainly generated by the two scalar scattering processes along the two fiber polarization axes. The corresponding two correlated photon states for the two scalar scattering processes are $|H_s\rangle|H_i\rangle$ and $|V_s\rangle|V_i\rangle$ respectively, where H and V denote two polarization directions along fiber axes, s and i denote signal and idler photons, respectively. However, $|H_s\rangle|H_i\rangle$ and $|V_s\rangle|V_i\rangle$ are not in quantum superposition due to the walk-off effect between fiber polarization axes.

To realize polarization entangled photon pair generation, the PM-DSF is split into two pieces of equal length and spliced together with 90 deg offset of fiber polarization axes, shown in Fig. 1(b). Under this condition, two pump components along polarization axes will walk off rapidly in the first fiber section, and then walk together at the end of the second fiber section. The vector scattering

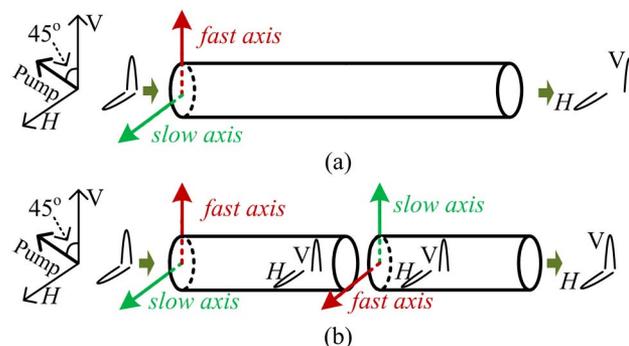


Fig. 1. (Color online) Scheme of polarization entangled photon pair generation in the PM-DSF.

process still can be suppressed effectively, thanks to the two pump components walking off entirely in the first part of the fiber. The $|H_s\rangle|H_i\rangle$ and $|V_s\rangle|V_i\rangle$ generated by the two scalar scattering processes overlap in space and time, since the walk-off effects in the two fiber sections cancel each other at the output end of the fiber. On the other hand, although the optical path in fiber is sensitive to environment, the optical path variations of the two pump polarization components along H and V can also cancel each other out in this proposed scheme. Hence, the phase difference between $|H_s\rangle|H_i\rangle$ and $|V_s\rangle|V_i\rangle$, denoted by ϕ , is stable at the output end of the PM-DSF, ensuring the quantum superposition of the two correlated photon states and realizing the generation of the polarization entangled state of $1/\sqrt{2}(|H_s\rangle|H_i\rangle + e^{i\phi}|V_s\rangle|V_i\rangle)$.

To demonstrate the vector scattering processes suppression in the scheme shown in Fig. 1(b), the photon flux spectral densities (PFSDs) of correlated photon pairs generated by the scalar and the vector scattering processes are compared theoretically utilizing the expressions deduced in [5], as shown in Eqs. (1) and (2):

$$\begin{aligned} f_{HH} &= (\gamma P_H L_s)^2 \sin^2 c^2 \left[(\beta_2 \Omega^2 + 2\gamma P_H) \frac{L_s}{2} \right], \\ f_{VV} &= (\gamma P_V L_s)^2 \sin^2 c^2 \left[(\beta_2 \Omega^2 + 2\gamma P_V) \frac{L_s}{2} \right], \end{aligned} \quad (1)$$

$$\begin{aligned} f_{HV} &= \frac{4}{9} (\gamma \sqrt{P_H P_V} L_v)^2 \\ &\quad \times \sin^2 c^2 \left[(\Delta\beta_1 \Omega + \beta_2 \Omega^2 + \gamma(P_H + P_V)) \frac{L_v}{2} \right], \\ f_{VH} &= \frac{4}{9} (\gamma \sqrt{P_H P_V} L_v)^2 \\ &\quad \times \sin^2 c^2 \left[(\Delta\beta_1 \Omega - \beta_2 \Omega^2 - \gamma(P_H + P_V)) \frac{L_v}{2} \right], \end{aligned} \quad (2)$$

where f_{HH} and f_{VV} are the PFSDs of two scalar scattering processes along H and V , respectively. f_{HV} and f_{VH} are the PFSDs of the two vector scattering processes in which the generated signal and idler photons are polarized along H and V or V and H , respectively. P_H and P_V are the powers of two pump components polarized along H and V , respectively. Ω is the frequency detuning between the pump wavelength and the wavelength of the signal or idler photons. γ is the optical nonlinear coefficient of the PM-DSF. $\Delta\beta_1$ and β_2 are group birefringence and group velocity dispersion of the PM-DSF at the pump wavelength, respectively. L_s and L_v are the effective lengths in which the scalar and the vector scattering processes could take place.

Parameters used in theoretical analysis refer to the experimental setup, where linearly polarized pump pulses with a pulse width of about 20 ps are injected into the PM-DSF (DS15-PS-U40A, fabricated by Fujikura Ltd.) with a 90 deg offset of the fiber polarization axes at the midpoint. L_s is 150 m, which is the exact total length of the fiber. $\Delta\beta_1$ of the PM-DSF is 0.286 ps/m, hence the two pump polarization components would walk off

entirely after a transmission of 7.5 m at the input end. Since the two pump polarization components would walk together at the output end of the second fiber section, L_v is about 15 m, i.e., double the walk-off length. β_2 and γ are -3.824 ps²/km and 3/W/km for PM-DSF used in the experiment. The total pump peak power is defined as P_p and the angle between the polarization direction of the pump light and H is defined as θ . The peak powers of the two pump polarization components, P_H and P_V could be obtained by $P_p \cos^2 \theta$ and $P_p \sin^2 \theta$, respectively.

The PFSDs of generated photon pairs by the scalar and the vector scattering processes under $P_p = 0.8$ W and $\theta = 45$ deg are shown in Fig. 2. The solid curve in the main figure of Fig. 2 is the PFSD of the total scalar scattering processes. The dashed curve in the inset of Fig. 2 is the PFSD of the total vector scattering processes. It can be seen that both scalar and vector scattering processes can generate photon pairs near the pump wavelength. However, the PFSD of the vector scattering processes is much lower than that of the scalar scattering processes due to $L_v \ll L_s$. The filters for the signal and idler photons in the experiment setup have a frequency detuning of 0.2 THz, which is indicated by the dotted-dashed curve in Fig. 2. It shows that under the frequency detuning of 0.2 THz the scalar scattering processes is about two orders of magnitude greater than the vector scattering processes. It demonstrates that the walk-off effect in the PM-DSF can provide sufficient suppression of the vector scattering processes, which is essential in the scheme to realize polarization entanglement generation.

The experimental setup for the proposed scheme is shown in Fig. 3, which is based on commercial components for optical communication. The pulsed pump is generated by a passive mode-locked fiber laser with a central wavelength of 1552.75 nm, a pulse width of about 20 ps, and a repetition rate of 1 MHz. A sideband rejection of >115 dB is achieved at the wavelengths of signal photons and idler photons. The polarization state of the pump is controlled by a polarizer (P), a rotatable half-wavelength plate (HWP1), and a polarization controller (PC1). A variable optical attenuator (VOA) and a 50/50 fiber coupler with a power meter (PM) are used to adjust and monitor the pump power. The PM-DSF is 150 m in length, submerged in liquid nitrogen (77 K)

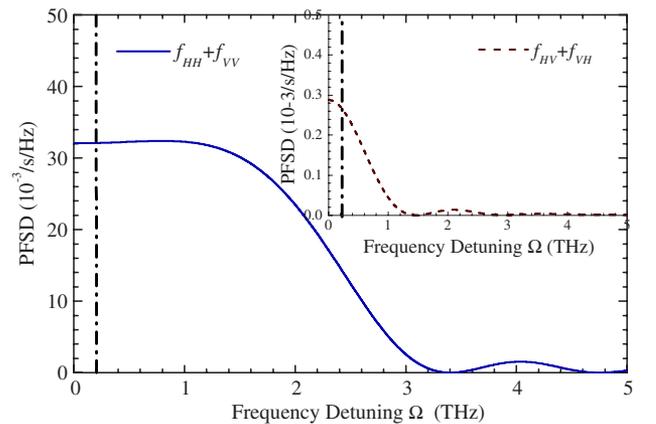


Fig. 2. (Color online) PFSD of generated photon pairs by the scalar and the vector scattering processes. In the main figure, $f_{HH} + f_{VV}$; in the inset, $f_{HV} + f_{VH}$.

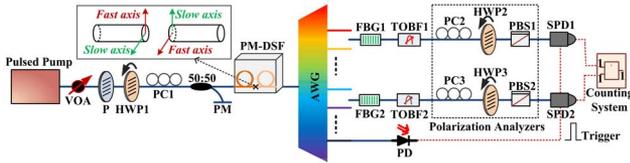


Fig. 3. (Color online) Experimental setup.

to suppress the impact of spontaneous Raman scattering (SpRS) process. The PM-DSF is divided into two pieces of equal length and then spliced together with a 90 deg offset of the fiber polarization axes. The output of PM-DSF is directed into a filtering and splitting system based on a 100 GHz/40 channel arrayed waveguide grating (AWG, Scion Photonics Inc.), two fiber Bragg gratings (FBGs), and two tunable optical band-pass filters (TOBFs). The total pump isolation is >110 dB at either signal (1555.15 nm) or idler wavelength (1550.35 nm). Two single-photon detectors (SPDs, Id Quantique, id201) are operated under Geiger mode with a detection window of 2.5 ns and are triggered with the residual pump detected by a photodetector (PD). The detection efficiencies of SPD1 and SPD2 are 21.83% and 22.56%, respectively.

In the experiment θ is adjusted to 45 deg for the maximum polarization entangled photon pair generation. To measure the polarization entanglement of generated photon pairs, two polarization analyzers are inserted before SPDs, shown in the dashed square in Fig. 3. Each of them consists of a PC, a rotatable HWP, and a polarizing beam splitter (PBS). The polarization direction of

the two polarization analyzers are adjusted through the method mentioned in [10], the detecting polarization direction of the signal and idler sides are denoted by θ_s and θ_i , which are adjusted by rotating the HWP2 and the HWP3, respectively.

Figure 4 shows the measured entanglement properties of generated photon pairs. Fig. 4(a) shows the idler side photon count rates under different θ_i , which are almost unchanged with θ_i , except for a small ripple caused by the polarization-dependent loss of the HWP3, demonstrating the polarization-indistinguishable property of the generated polarization-entangled photon pairs. The single count rate is about 10^{-3} per pulse, ensuring that the possibility of a multiphoton pair event is sufficiently low in the experiment. Fig. 3(b) shows the results of coincidence counts per 10 seconds (without subtracting the background count) under different θ_i . Squares and circles are experimental data, while θ_s is set to 0 and 135 deg, respectively. Solid and dashed curves are fitting curves, showing that the visibilities of two-photon interference (TPI) fringes are $92 \pm 3\%$ and $89 \pm 3\%$ for $\theta_s = 0$ and 135 deg, respectively. Hence, the proposed scheme of polarization-entangled photon pair generation based on commercial PM-DSF is demonstrated by the experiment results of the indistinguishable property on the single side and TPI in two nonorthogonal polarization bases.

In summary, a linear scheme to generate polarization-entangled photon pairs at $1.5 \mu\text{m}$ based on commercial PM-DSF is proposed and demonstrated experimentally. The birefringent walk-off effect in the PM-DSF provides an effective way to suppress the vector scattering processes in the fiber. A 90 deg offset of the fiber polarization axes is introduced at the midpoint of the fiber to realize the quantum superposition of the two correlated photon states generated by the two scalar processes along the fiber polarization axes. A TPI fringe visibility of $89 \pm 3\%$ is achieved without subtracting the background counts, showing the great potential of the proposed scheme in developing an efficient and stable fiber-based polarization-entangled quantum light source at optical communication band.

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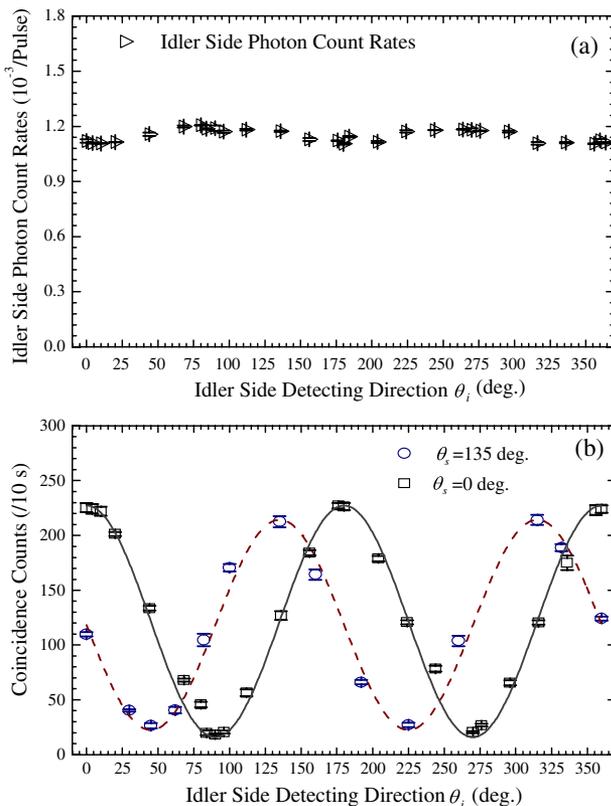


Fig. 4. (Color online) (a) Idler side photon count rates under different θ_i ; (b) Coincidence counts under different θ_i .