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Experimental Study on Preparation Efficiency of Microstructured-Fibre Based Heralded Single-Photon Source at 1.5 μm *

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We present an experimental study on the microstructured-fibre (MSF) based heralded single photon source (HSPS) at 1.5 μm. The preparation efficiency is measured to be 8.7% under room temperature. The analysis of the experimental results shows that the preparation efficiency can be improved up to 22.9% by the Raman noise suppression with fibre cooling under the experimental setup parameters. Further efficiency improvement could be achieved by improving the collection efficiency and reducing dark counts of single photon detectors (SPDs). The experimental results and analysis show great potential applications of the MSF in high efficient HSPSs.

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Single-photon sources (SPSs) with high fidelity are essential devices in quantum information processing including quantum key distribution (QKD),[1] linear optics quantum computation (LOQC),[2] and so on. Weak coherent pulse (WCP) light has been used as a reliable single photon source in many experiments. However, since the photon number in each pulse satisfies the Poisson distribution principle, the average photon number in each pulse should be lower than 0.1 to reduce the possibility of the multi-photon generation. It will lead to a high proportion of the empty pulse and limit the performance of quantum communication and information systems.[3]

In recent years, several ways to realize high performance single photon sources are reported, among which the heralded single photon source (HSPS) attracts much attention due to its high performance in the single photon generation and availability by mature techniques. The principle of the HSPS is based on the quantum correlated photon pair. If one photon of the pair is detected by a single photon detector (SPD), it can provide a trigger to herald the existence of another photon of the pair. Compared to the WCP, it eliminates the empty pulse possibility by selecting pulses with photons by triggers. Recently, a decoy-state QKD scheme has been experimentally demonstrated using HSPS over a distance of 25 km, which shows the great potential of HSPSs in QKD systems.[4]

Spontaneous parametric down conversion (SPDC) process in bulk crystals and crystal waveguides have been demonstrated as feasible ways to realize HSPSs.[5,6] However, difficulties in the single photon spatial collection limit their performance. Recently, the correlated photon pair generation based on the spontaneous parametric fluorescence (SPF) in dispersion shift fibres (DSFs) and microstructured fibres (MSFs) has been demonstrated experimentally.[7−11] Especially, MSFs have advantages of high nonlinearity and the flexibility in dispersion design, thanks to their air-hole structure in fibre cross sections,[12] which is preferred in the fibre based correlated photon pair generation. To suppress noise photons of spontaneous Raman scattering (SpRS), an experiment of the fibre based HSPS has been reported using a piece of MSF with a zero-dispersion wavelength (ZDW) around 1 μm, in which the correlated photon pair is generated and filtered out at wavelengths with low Raman noise.[11] On the other hand, fibre cooling has been proven to be an effective way to reduce Raman photons, which provides another possible way to realize fibre based HSPSs of high performance when the two photons of the correlated photon pair generated in MSFs are all in 1.5 μm band.

In this Letter, an experimental study on the MSF based HSPS at 1.5 μm is presented. The preparation efficiency under different pump power is calculated by the measured photon counts. Using the experimental results, we calculate the Raman noise under different temperatures and demonstrate the effect of fibre cooling to improve the preparation efficiency. The impact of the heralded single photon collection efficiency and dark counts of SPDs is also discussed. The analysis shows the feasibility of the high efficient MSF based HSPS at 1.5 μm.

Figure 1 shows the experimental setup. The high nonlinear MSF (fabricated by Crystal fibre A/S Inc.) is 25 m in length, with a measured nonlinear coefficient

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γ of 66.7 $W^{-1}km^{-1}$ and a ZDW around 1565 nm.[12] The pulsed pump is generated by a passive mode locked fibre laser with a repetition of 1 MHz and a central wavelength of 1552.75 nm, which is in the anomalous dispersion region of the MSF. After filtered by fibre Bragg gratings (FBGs) and tunable bandpass filters (TBPFs), the sideband suppression of the pump light is higher than 120 dB. A variable optical attenuator (VOA) is used to adjust the pump power and a polarization controller (PC) is used to ensure the pump's polarization along the principal axis of the MSF.

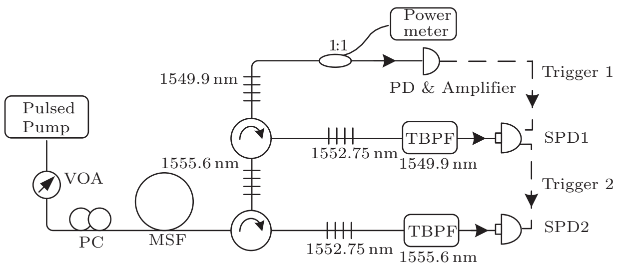

Fig. 1. Experimental setup.

As pump pulses pass through the MSF, correlated photon pairs are generated by the SPF process. The SPF is a third-order nonlinear parametric process, in which two pump photons are annihilated, while a pair of fluorescence photons is generated. The two generated photons are denoted as signal and idler, respectively, and their frequencies are higher or lower than the pump photon frequency. The SPF process should satisfy the energy-conservation and moment-conservation, which decide the frequencies of signal and idler photons. According to the energy-conservation, the relation of frequencies of pump, signal and idler photons (denoted by ω_p, ω_s and ω_i, respectively) is $2\omega_p = \omega_s + \omega_i$.

In our experiment, the wavelengths of signal and idler photons are 1549.9 nm and 1555.6 nm, respectively. The filter system after the MSF splits signal photons, idler photons and residual pump pulses to different detectors. Signal and idler photons are filtered out by filter systems based on FBGs, circulators and TBPFs and then sent to single photon detectors (SPD1 and SPD2). Meanwhile, the residual pump pulses are sent to a power meter and a photon detector (PD) through a 1:1 coupler. The electrical pulse series output from the PD are amplified and used as trigger signals for the SPD1. SPD1 and SPD2 are both operated in the gated Geiger mode, with a detection window width of 2.5 ns and a dead time of 10 μs. To realize the HSPS, only SPD1 is triggered by the PD. When the SPD1 has detected a signal photon in its detection window, it will send an electrical pulse to trigger the detection window of the SPD2 for the idler photon.

Three photon counts are measured in the experiment. Photon counts of the SPD1 represent heralding counts per pulse of the HSPS, which is denoted by N_s since the SPD1 detects signal photons. Since the SPD2 is triggered by the SPD1, photon counts of SPD2 represent coincidence counts per pulse. By adjusting the fibre length before the SPD2, coincidence counts per pulse and accidental-coincidence counts per pulse, which are denoted by P_{co} and P_{ac}, can be measured under the conditions that two SPDs detect photons generated by the same pump pulse and by different pump pulses, respectively. All photon counts are measured during a counting time of 30 s and averaged after measurement of 5 times.

Several physical processes determine the measured photon counts in the experiment. The SPF process in the MSF is the contribution to realize the heralded single photon generation. The correlated photon pair number per pulse is denoted by R. On the other hand, since the pump wavelength is in the anomalous dispersion region of the MSF, the generated signal and idler photons are close to the pump light in spectrum. Hence, SpRS can not be neglected at the signal and idler wavelengths. The Raman photon number per pulse at signal and idler wavelengths are denoted as R_s and R_i, respectively. Another noise contribution is dark counts of two SPDs, which are denoted by d_s and d_i for the SPD1 and SPD2, respectively. The measured photon counts are also determined by collection efficiencies of signal and idler photons, which include the losses of the filter system after the MSF and detection efficiencies of two SPDs. Collection efficiencies are denoted by η_s and η_i for signal and idler photons, respectively. Hence, three measured photon counts can be expressed as

$$\begin{aligned} N_s &= \eta_s(R+R_s)+d_s, \\ P_{co} &= \eta_s\eta_i(R+RR_i+RR_s+R_sR_i) \\ &\quad +\eta_s(R+R_s)d_i+d_s\eta_i(R+R_i)+d_sd_i, \\ P_{ac} &= \eta_s\eta_i(R^2+RR_i+RR_s+R_sR_i) \\ &\quad +\eta_s(R+R_s)d_i+d_s\eta_i(R+R_i)+d_sd_i. \end{aligned} \tag{1}$$

Since dark counts and collection efficiencies have been measured during the experimental setup preparation ($d_s = 1.5\times10^{-4}$, $d_i = 1.17\times10^{-4}$, $\eta_s = 3.17\%$ and $\eta_i = 4.39\%$), R, R_s and R_i can be calculated from the measured results according to Eq. (1).

In the experiment, we measure all photon counts under the condition of low pump power, under which the correlated photon pair generation rate is in the scale of about 10^{-3} per pump pulse. Here, we focus our attention on the preparation efficiency of the HSPS, which is denoted by η_p and determined by

$$\eta_p = \frac{P_{co}}{\eta_{\rm SPD2}\cdot N_s}, \tag{2}$$

where η_{SPD2} is the detection efficiency of the SPD2 (efficiencies of both SPDs are set to 15% in the experiment).

Figure 2 shows the measured P_{co} and P_{ac} under different heralding counts N_s per pulse. The inset is the measured heralding counts N_s per pulse with the increasing pump power. It can be seen that all the measured photon counts increase with the pump power. P_{co} is obviously higher than P_{ac}, demonstrating the generation of correlated photon pairs in the MSF. In the experiment, the largest preparation efficiency η_p is 8.7%, with a heralded single-photon rate of 38.2 Hz/s.

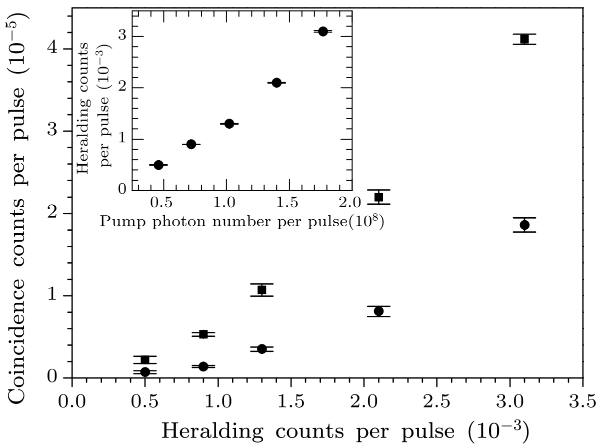

Fig. 2. Coincidence counts (square) and accidental-coincidence counts (circle) under different heralding counts. The inset shows the measured heralding counts per pulse with increasing pump power.

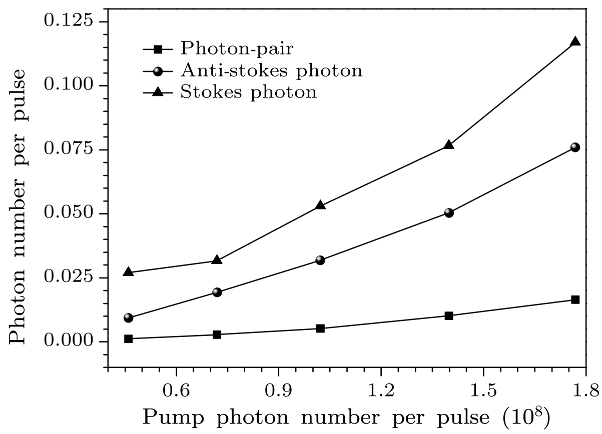

Fig. 3. Photon pair number, stokes and anti-stokes photon number under different pump power levels.

Although the measured preparation efficiency η_p is limited, the experimental results can be used to analyse the potential of the MSF based HSPS. Firstly, R, R_s and R_i can be calculated from the measured results, as shown in Fig. 3. It can be seen that all the photon number per pump pulse is less than 0.1, which ensure that the possibility of the multi-photon generation is sufficient low. The Raman photon number is always higher than the photon pair number, showing that the Raman noise dominates in the measured photon counts, which limits the HSPS performance seriously.

Fibre cooling has been proven to be an effective way to suppress the Raman noise in fibres.[14] The Raman photon number is related to the fibre's temperature. Since the signal and idler wavelengths are at anti-stokes and stokes sidebands of SpRS respectively, the Raman photon number has the relations[15]

$$R_s \propto \varphi(T, \Omega_s), \quad R_i \propto \varphi(T, \Omega_s) + 1, \tag{3}$$

where

$$\varphi(T, \Omega_s) = \left[\exp\left(\frac{h|\Omega_s|}{k_B T}\right) - 1\right]^{-1}, \tag{4}$$

is the Bose-Einstein temperature-dependant correction factor; Ω_s, T, h and k_B are the frequency detuning, temperature, Planck's constant and Boltzmann's constant, respectively. Considering $\Omega_s = 355$ GHz in the experiment, we can calculate the Raman photon suppression under the temperature of liquid nitrogen (77 K) and liquid helium (4 K) respectively, as listed in Table 1.

Table 1. Raman photon number suppression at different temperatures.

$R_s(77\,\text{K})/R_s(300\,\text{K})$	0.236
$R_i(77\text{K})/R_i(300\,\text{K})$	0.2782
$R_s(4\,\text{K})/R_s(300\,\text{K})$	0.000834
$R_i(4\,\text{K})/R_i(300\,\text{K})$	0.0561

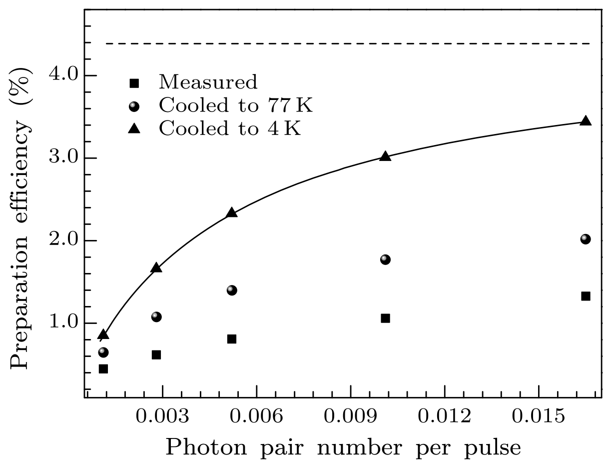

Fig. 4. Preparation efficiency versus photon pair number at different temperatures.

Figure 4 shows the calculated η_p under the Raman photon suppression listed in Table 1 and the parameters of the experimental setup. It can be seen that the preparation efficiency increases with the photon pair number at all the temperature. The lower the temperature, the higher the efficiency. Under the temperature of 4 K, the calculated data agree with the solid line, which is the theoretical result under the assumption that no Raman noise is generated. The highest efficiency under the liquid helium fibre cooling is 22.9%, which is limited by the parameters of the experimental setup.

To show the impact of the parameters of the experimental setup, we plot the theoretical result considering only collection efficiencies as the dashed line in the figure, which neglects not only the Raman noise but also dark counts of SPDs. Compared to the solid line, it is seen that the impact of collection efficiency is not related to the photon pair number, i.e. the pump level. On the other hand, dark counts will deteriorate the preparation efficiency at low pump power. Hence, further efficiency improvement should be achieved by reducing collection losses and dark counts of SPDs, and selecting a proper pump level, high enough to reduce the impact of dark counts and low enough to avoid the multi-photon generation.

It worth noting that, although the second-order autocorrelation function $g^{(2)}(0)$ is not measured due to the limited experimental condition (a lack of one SPD), it can be calculated according to the measured R, R_s, R_i and their photon number distributions of thermal statistics.[6] In the case that the temperature is 300 K and the HSPS rate is 38.2 Hz/s, we have $g^{(2)}(0) = 0.841$, which is mainly due to the Raman noise. If the temperature decreases to 4 K, $g^{(2)}(0) = 0.104$, which is limited by collection losses and dark counts of the SPDs. Hence, further reducing collection losses and dark counts of SPDs can also improve the HSPS performance.

In conclusion, we have reported an experimental research on the MSF based HSPS at 1.5 μm. The preparation efficiency is measured to be 8.7% under room temperature. The analysis of the experimental results shows that the preparation efficiency can be improved up to 22.9% with the Raman noise suppression by fibre cooling under the parameters of the experimental setup. Further efficiency improvement could be achieved by improving the collection efficiency and reducing dark counts of SPDs. The experimental results and analysis show that the MSF has great potential applications in high efficient HSPSs.

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