High-Quality Fiber-Based Heralded Single-Photon Source at 1.5 μm

2012 Chinese Phys. Lett. 29 054215

(http://iopscience.iop.org/0256-307X/29/5/054215)

CHIN. PHYS. LETT. Vol. 29, No. 5 (2012) 054215

High-Quality Fiber-Based Heralded Single-Photon Source at 1.5 μm *

WANG Peng-Xiang(王鹏祥), ZHOU Qiang(周强), ZHANG Wei(张巍)**,
HUANG Yi-Dong(黄翊东), PENG Jiang-De(彭江得)

Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084

(Received 20 January 2012)

A high-quality heralded single-photon source (HSPS) at 1.5 μm is experimentally demonstrated based on spontaneous four wave-mixing in a piece of dispersion-shifted fiber cooled by liquid nitrogen. To improve the up-limit of the preparation efficiency of the HSPS, commercial dense wavelength-division multiplexing components are used to reduce the loss of the filtering and splitting system between the fiber and the single-photon detectors. As a result, a preparation efficiency of 80% is realized under a $g^{(2)}(0)$ *of 0.06 in our HSPS experimental system, which is the best performance for the fiber-based HSPS at 1.5 μm reported so far.*

PACS: 42.50.Ex, 42.65.Lm DOI: 10.1088/0256-307X/29/5/054215

Single-photon sources at 1.5 μm have important applications in quantum communication and quantum information processing,[1−4] since they provide single photon generation at a low-loss transmission window of commercial optical fibers. The traditional way of obtaining single photons is through attenuating the laser power sufficiently to single-photon levels. The statistics of output photons of the attenuated laser source satisfies Poissonian distribution.[5] As a result, in certain detecting windows, multi-photon generation cannot be avoided and impairs the performance of single-photon generation. For the attenuated laser source, the only way to reduce the possibility of multi-photon generation is to increase the attenuation, thereby reducing the average photon number in each detecting window. However, this would increase the possibility of there being no photon in the detecting window, leading to a low single-photon generation efficiency. Recently, more and more attention focuses on the heralded single-photon source (HSPS), since it provides a way to solve the intrinsical defect of the attenuated laser source. The HSPS is based on correlated photon-pair (CPP) generation by spontaneous nonlinear parametric processes. In the HSPS, one photon of the correlated photon pair is detected, providing an electrical trigger signal to herald the arrival of the other photon. The electrical trigger signal can be used to control the detecting window of single-photon detection, which would greatly reduce the possibility of there being no photon arrival whilst the detecting window is open. To date, several schemes of the HSPS at 1.5 μm have been proposed, such as spontaneous parametric down-conversion (SPDC) in bulk nonlinear optical crystals, SPDC in periodically poled crystal waveguides and atomic cascades.[6−9] However, more convenient schemes compatible with current optical networking technology are expected for real application in quantum engineering.[10,11]

Recently, 1.5 μm correlated photon-pair generation through spontaneous four wave-mixing (SFWM) in optical fibers has received much attention. It is based on commercial fibers and optical components of optical communication systems, providing a practical way to realize the HSPS at 1.5 μm. In our previous work,[12] a fiber-based HSPS with a preparation efficiency of 60% and a $g^{(2)}(0)$ of 0.06 was achieved, showing the feasibility of high-quality single-photon generation. On the other hand, this work showed that the preparing efficiency of the fiber-based HSPSs was decided by the loss of the filtering and splitting system between the nonlinear fiber and the single-photon detector and noise photons generated by spontaneous Raman scattering (SpRS). Considering that the impact of SpRS can be suppressed by fiber-cooling techniques,[13,14] the loss of the filtering and splitting system will decide the theoretical up-limit of the HSPS efficiency.

In this Letter, we optimize the filtering and splitting system utilizing commercial dense wavelength-division multiplexing (DWDM) components to improve the theoretical up-limit of the HSPS preparation efficiency. As a result, the preparation efficiency of the HSPS is improved from 60% to 80% while $g^{(2)}(0)$ is at the same level of 0.06, which is the best performance for the fiber-based HSPS at 1.5 μm to our knowledge.

The experimental setup of the fiber-based HSPS at 1.5 μm is shown in Fig. 1. The pulsed pump light is generated by a mode-locked erbium-doped fiber laser (ML-EDFL) with a repetition rate of 1 MHz and a central wavelength of 1552.52 nm. The pump light then passes through a filter system, including a fiber Bragg grating (FBG), a circulator, and three DWDMs at 1552.52 nm (ITU-C31), to narrow its linewidth to 0.2 nm and enhance its side-band rejection to 120 dB at wavelengths where the signal and idler photon-detection is performed. The pulse width of the output

*Supported by the National Basic Research Program of China under Grant Nos 2011CBA00303 and 2010CB327606, Tsinghua University Initiative Scientific Research Program and Basic Research Foundation of Tsinghua National Laboratory for Information Science and Technology (TNList).
**Corresponding author. Email: zwei@tsinghua.edu.cn

pump light is about several tens of picosecond (estimated by the linewidth). A variable optical attenuator (VOA) and a 1:1 fiber coupler with a power meter (PM) are used to monitor and control the power level of the pump light before it is launched into the optical fiber.

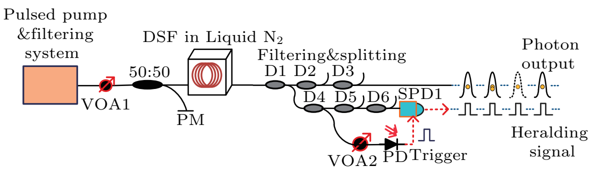

Fig. 1. Experimental setup of the fiber-based HSPS at 1.5 µm. VOA: variable optical attenuator; PM: power meter; PD: photo detector; DSF: dispersion-shifted fiber; SPD: single-photon detector; D1∼D6: DWDMs.

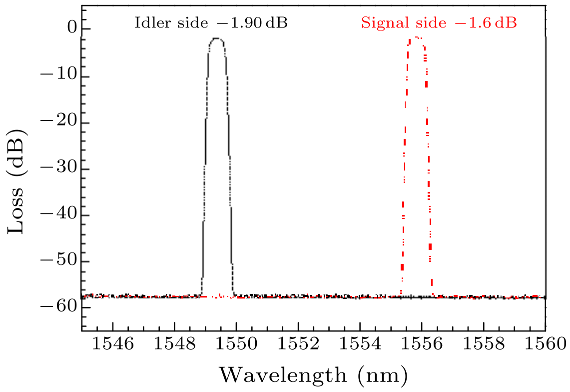

Fig. 2. The transmission spectra of the filtering and splitting system. Dashed line: signal side; solid line: idler side.

The fiber used in the experiment is a piece of commercial dispersion-shifted fiber (made by Yangtze Optical Fiber and Cable Company Ltd). The fiber is 500 m in length, and is cooled by liquid nitrogen to suppress SpRS. The generated CPPs by the SFWM processes in the fiber and residual pump light are separated by a filtering and splitting system based on commercial DWDM components, as shown by D1–D6 in Fig. 1. The central wavelength of signal and idler photons are at 1555.75 nm and 1549.32 nm, i.e., the ITU channel of C27 and C35, respectively. Figure 2 shows the measured transmission spectra of the filtering and splitting system, and the black and red lines are the results of the idler and signal sides, respectively. They are measured by a wavelength-tunable laser (Santec 510) and a power meter (Agilent 82336). The insertion loss of the signal side is −1.6 dB, while that of the idler side is −1.9 dB. The up-limit of the HSPS preparation efficiency is decided by the loss of the heralded photon before detection.[12] Hence, in the experiment the signal-photon side is used as the heralded photon output end, while the idler-photon side is used to provide the heralding signal. Compared with the work of Ref. [12], the loss of the heralded photon output end is reduced by 1 dB, leading to about 20% improvement of the preparation efficiency. The obtained side-band rejection of the filtering and splitting system is only ∼55 dB on both sides, as shown in Fig. 2, which is limited by the dynamic range of the measuring system. In fact, a pump light isolation of more than 120 dB can be achieved on either signal or idler photon side, since at least three DWDMs are cascaded on both sides, and each DWDM has more than 40 dB pump-light isolation and high-return loss. As a result, the impact of residual pump light can be neglected in the experiment.

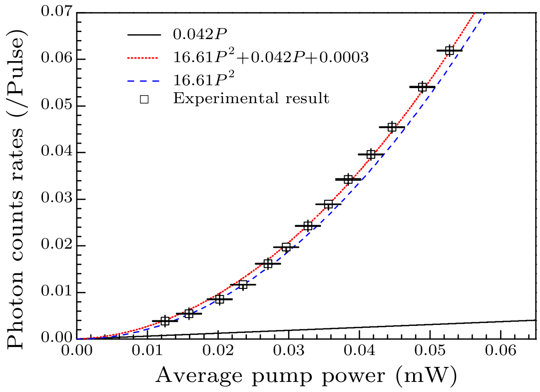

Fig. 3. The photon-count rate at the idler side under different pump levels. Square dots: experimental data; dotted line: fitting curve of experimental data; dashed line: contribution of the CPPs; solid line: contribution of the SpRS and residual pump.

The generated photons are detected by commercial single-photon detectors (SPDs, ID Quantique, id201) based on an InGaAs/InP avalanche photodiode. The SPDs are operated in gated Geiger mode with a detection window width of 2.5 ns. The residual pump light is detected by a photon detector (PD) to provide the trigger signals for the SPDs. The detection efficiencies of SPDs 1, 2 and 3 are 15.21%, 14.85 % and 14.23%, respectively. In the experiment, each measured photon-count rate is a statistical result of five measurements with a single count time of 30 s.

Firstly, the single-side photon-count rates at the idler side under different pump levels are measured by SPD1 and shown in Fig. 3. The square dots are experimental data, while the dotted line is the fitting curve using a polynomial of $aP^2 + bP + c$. Here P is the pump level; a, b and c are the fitting parameters. The quadratic term in the polynomial represents the contribution of CPP generation by SFWM, which is shown by the dashed curve in Fig. 3. The linear term represents the impacts of SpRS and residual pump photons, shown by the solid line in Fig. 3. The constant term represents the dark counts of SPD1, which can almost be ignored. It can be seen that the contribution of CPP generation is far higher than the impact of SpRS and residual pump photons when the single-side photon-count rate is greater than 0.01 per pulse. The high-quality CPP generation ensures the high performance of the HSPS based on our experimental system.

The experimental setup was then adjusted to realize the HSPS, in which SPD1 detects idler-side photons in order to provide a heralding signal for the heralded photon output on the signal side. To measure the preparation efficiency of the HSPS, the heralded photons on the signal side are detected by SPD2, which is triggered by the heralding signal from SPD1. The preparation efficiency can be calculated by $R_2/(R_1\eta_2)$, where R_1 and R_2 are the photon-count rates of SPD1 and SPD2, respectively; η_2 is the detection efficiency of SPD2. The measured preparation efficiencies under different idler-side photon-count rates are shown in Fig. 4. It can be seen that when the idler-side photon-count rate is small under low pump level, the impacts of SpRS and residual pump photons seriously limit the preparation efficiency of the HSPS. As the pump level increases, the CPPs gradually dominate the generated photons, leading to an increase in the preparation efficiency. If the pump level is too high to neglect the possibility of multi-photon generation, the preparation efficiency would continue to increase with the pump level and finally be close to one.

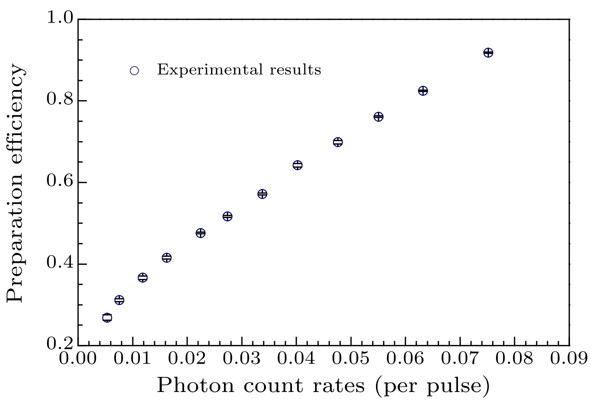

Fig. 4. The measured preparation efficiency of the HSPS versus idler-side photon-count rate.

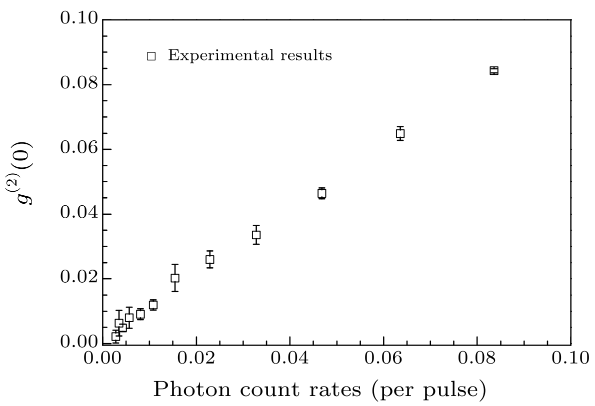

Fig. 5. The measured $g^{(2)}(0)$ of the HSPS versus idler-side photon-count rate.

However, the pump level cannot increase unlimitedly since the multi-photon generation reduces the quality of the single-photon generation in HSPS, which is described by the second-order correlation function $g^{(2)}(0)$. The $g^{(2)}(0)$ was measured by the Hanbury–Brown and Twiss setup,[15] in which the heralded photons of the HSPS are split by a 1:1 fiber coupler and detected by two single-photon detectors (SPD2 and SPD3), respectively. The detection windows of SPD2 and SPD3 are triggered by the heralding signal provided by the SPD1. The $g^{(2)}(0)$ is calculated by $R_{23}/(R_2R_3)$, where R_2 and R_3 are the photon-count rates of SPD2 and SPD3, respectively, and R_{23} is the coincident photon-count rate of SPD2 and SPD3.[12] Figure 5 shows the measured $g^{(2)}(0)$ of the HSPS under different idler-side photon-count rates. It can be seen that $g^{(2)}(0)$ also increases with the increasing idler-side photon-count rates. Hence, the pump level should be optimized to take trade-off between the preparation efficiency and the $g^{(2)}(0)$ of the HSPS. If the $g^{(2)}(0)$ is set to 0.06, it can be concluded from Figs. 4 and 5 that the preparation efficiency of the HSPS is about 80%, showing a high improvement in the performance of the HSPS compared with that of the previous work.[12]

To show the HSPS performance more clearly, we calculate the possibilities of zero-, single- and multi-photon events when a heralding signal arrives under a preparation efficiency of 80% and a $g^{(2)}(0)$ of 0.06. The single-photon generation possibility is as high as 78.2%, while the possibilities of zero-photon and multi-photon generation are 20% and 1.8%, respectively. It is the best performance of the fiber-based HSPS operating at 1.5 μm to our knowledge, showing its great potential in applications of quantum communication and quantum information.

References

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

[2] O'Brien J L, Furusawa A and Vuckovic J A 2009 *Nature Photon.* **3** 687

[3] Kok P, Munro W J, Nemoto K, Ralph T C, Dowling J P and Milburn G L 2007 *Rev. Mod. Phys.* **79** 135

[4] Wang Q, Chen W, Xavier G, Swillo M, Zhang T, Sauge S, Tengner M, Han Z, Guo G and Karlsson A 2008 *Phys. Rev. Lett.* **100** 090501

[5] Mandel L and Wolf E 1995 *Optical Coherence and Quantum Optics* (Cambridge: Cambridge University Press) chapter 22.4.7 p 1084

[6] Hong C K and Mandel L 1986 *Phys. Rev. Lett.* **56** 58

[7] U'Ren A B, Silberhorn C, Ball J L, Banaszek K and Walmsley I A 2005 *Phys. Rev.* A **72** 021802(R)

[8] Grangier P, Roger G and Aspect A 1986 *Europhys. Lett.* **1** 173

[9] Alibart O, Ostrowsky D B and Baldi P 2005 *Opt. Lett.* **12** 1539

[10] Chapuran T E, Toliver P, Peters N A, Jackel J, Goodman M S, Runser R J, McNown S R, Dallmann N, Hughes R J, McCabe K P, Nordholt J E, Peterson C G, Tyagi K T, Mercer L and Dardy H 2009 *New J. Phys.* **11** 105001

[11] Zhang S T, Zhang W, Zhou Q, Huang Y D and Peng J D 2009 *Chin. Phys. Lett.* **26** 034206

[12] Zhou Q, Zhang W, Cheng J R, Huang Y D and Peng J D 2011 *Phys. Lett.* A **375** 2274

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

[14] Dyer S D, Baek B and Nam S W 2009 *Opt. Express* **17** 10290

[15] Brown H R and Twiss R Q 1956 *Nature* **178** 1046