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Optical-fiber based source of correlated photons at ~925 nm for satellite QKD applications

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ABSTRACT

Optical-fiber based pulsed source of correlated photons is proposed and investigated experimentally. Characteristics and operation of the source is discussed. Single photon generation rate up to 460 000 photons/s at ~925 nm wavelength is demonstrated experimentally.

Keywords: Optical fiber, ultrashort pulses, four-wave mixing, single-photon source, correlated photon-pair source

1. INTRODUCTION

For deployment of satellite quantum key distribution (QKD) systems, compact and robust sources of entangled photon pairs are required [1]. In conventional approach, entangled photon generation is realized using bulk crystals and free-space optics [2], which is not very robust solution. Therefore, such sources would benefit from optical fiber-based configurations, which by design are more robust and reliable. However, fused silica optical fibers intrinsically lack second-order nonlinearity, therefore the spontaneous parametric down-conversion process, which is utilized in bulk crystals for photon-pair generation, is not possible in conventional fibers. Nevertheless, second-order nonlinearity can be induced in optical fibers by thermal poling [3] and there is ongoing research related to suitability of such fibers for entangled-photon generation [4–6]. Unfortunately, generation of photon pairs in thermally-poled fibers is possible only for non-polarization-maintaining fiber configurations, and this means that sustainability of polarization states is sensitive to variations of environmental parameters, which greatly limits the robustness and applicability of such sources. Photon-pair generation in conventional fused silica fibers can also be implemented by utilizing third-order nonlinear process such as spontaneous four-wave mixing (FWM). For this process to occur effectively, phase-matching conditions have to be satisfied for interacting waves. Achieving phase-matching at required wavelength can be challenging, so fiber with engineered dispersion parameters, such as photonic crystal fibers (PCF) are often used for such purposes. So far, FWM in photonic crystal fibers has been demonstrated both as a means for wavelength conversion (in classical limit) [7–9] and as a means for photon-pair generation [10–12]. In this work we propose design of optical fiber-based source of correlated photons, which relies on four-wave mixing nonlinear process in the fiber and was designed to provide signal/idler photons at wavelength region near ~925nm, which is covered by technologically mature and efficient silicon avalanche photodiode-based single-photon detectors. The source operates in pulsed mode and provides correlated signal and idler photons, which, after some modifications of the setup, can potentially be suitable for QKD applications. Here we present experimental results of operation characteristics and achievable single-photon generation performance of the proposed source.

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2. EXPERIMENTAL SETUP

Schematic diagram of the proposed source is shown in Figure 1. It consists of few main blocks: Optical pulse generator, fiber amplifier, wavelength conversion stage and correlated photon generation stage. Optical pulse generator was based on self-phase modulation in optical fiber and alternating spectral filtering [13] and provided 1030 nm center wavelength, picosecond pulses at 15 MHz repetition rate. Two outputs were available from the pulse generator. Pulses from one output were used for synchronization channel. Pulses from main output were further amplified in fiber amplifier stage and directed to wavelength conversion stage. In wavelength conversion stage, pulse wavelength was converted to ~925 nm by means of FWM process in photonic crystal fiber SC-5.0-1040-PM (NKT Photonics). These pulses were then used as a pump for correlated photon generation stage. In between stages, some free-space components were used for spectral filtering and pump pulse conditioning, however, these components could also be replaced with fiber-based solution in final system configuration. In correlated photon generation stage, idler and signal photons were generated by means of FWM process in photonic crystal fiber NL-PM-750 (NKT Photonics). After that, signal and idler photons were separated by using interference optical filters.

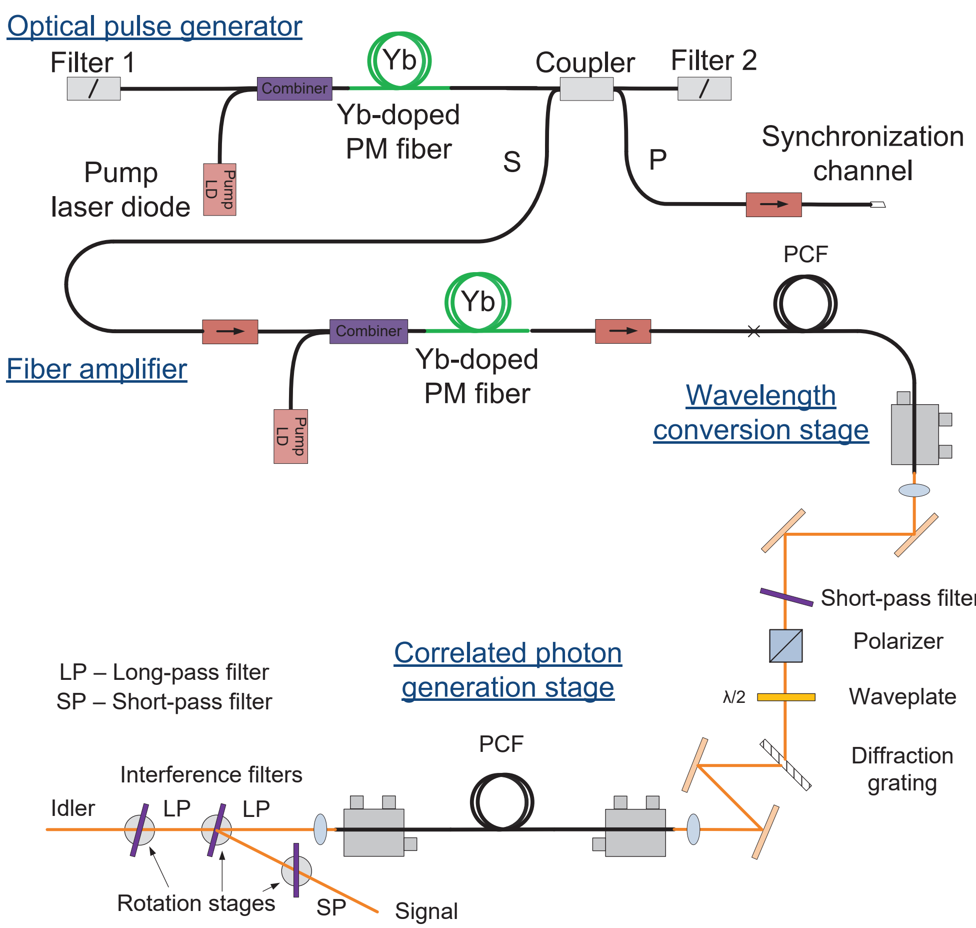

Figure 1. Schematic diagram of experimental setup of proposed source of correlated photons.

3. CHARACTERIZATION OF GENERATED PULSES

Optimized configuration of optical pulse generator provided pulses with ~1 ps duration at 1030 nm center wavelength. Pulse repetition rate was 15 MHz. Measured average output power and pulse energy from both of pulse generator outputs is shown in Figure 2. These pulses were then amplified in fiber amplifier stage in order to boost pulse energy up to the level required for wavelength conversion by means of FWM.

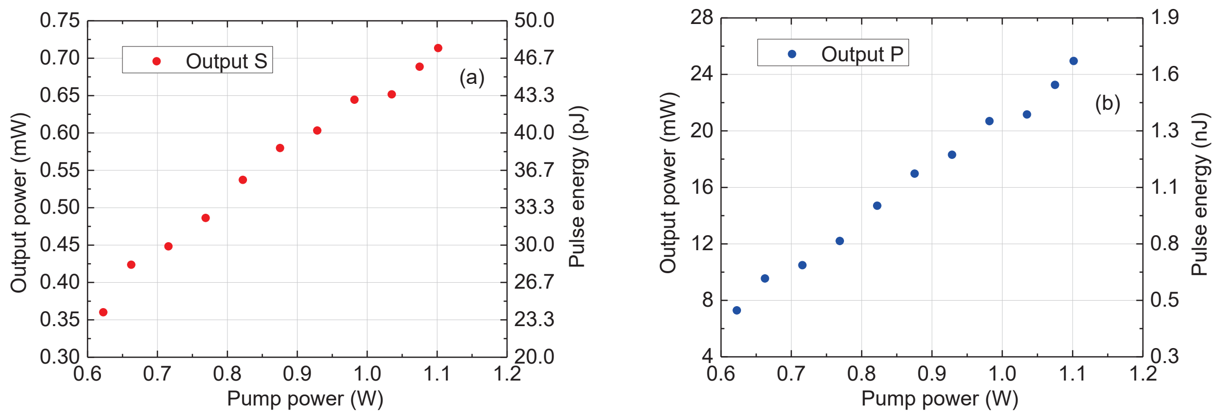

Figure 2. Measured output power and pulse energy versus pump power from output S (a) and P (b) of the optical pulse generator setup.

Pulse amplification experiments showed that pulse energy can be boosted up to 60 nJ (Figure 3). However, it was also registered that with increase of pulse energy, pulse spectrum is strongly broadened because of self-phase modulation (SPM) in the fiber. Such spectral broadening has negative influence for FWM-based wavelength conversion, therefore pulse energy had to be further optimized according to wavelength conversion results.

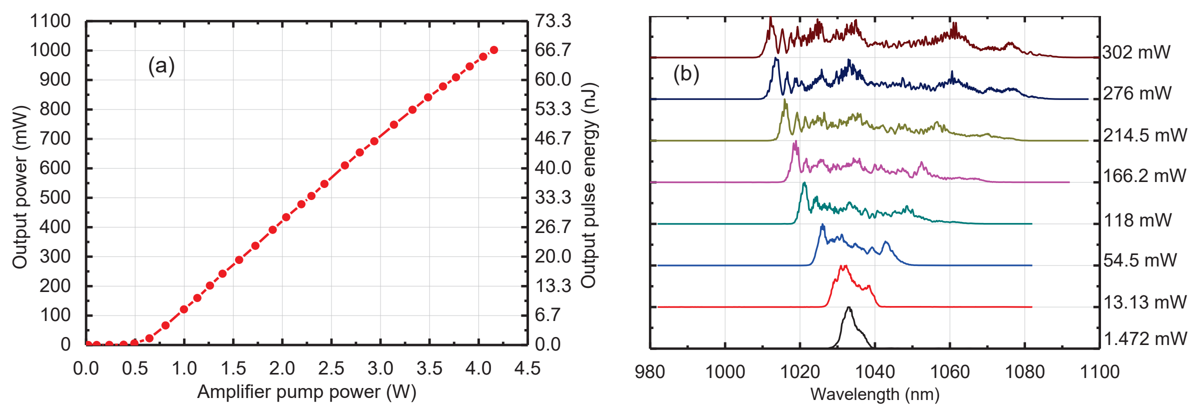

Figure 3. a) Measured output power and pulse energy versus pump power from the fiber amplifier stage; b) Measured output spectra from the fiber amplifier stage at different output power levels.

Wavelength conversion experiments were carried, and pulse parameters were optimized accordingly. It was found that up to 8 % conversion efficiency to spectral region around ~900 nm is achievable (Figure 4a). However, at conversion efficiencies > 2% (pump average power > 200 mW and pulse energy >13.3 nJ), significant spectral broadening of pulses at 900 nm was visible (Figure 4b) which is undesirable. Measured pulse duration at ~900 nm wavelength was 300 fs.

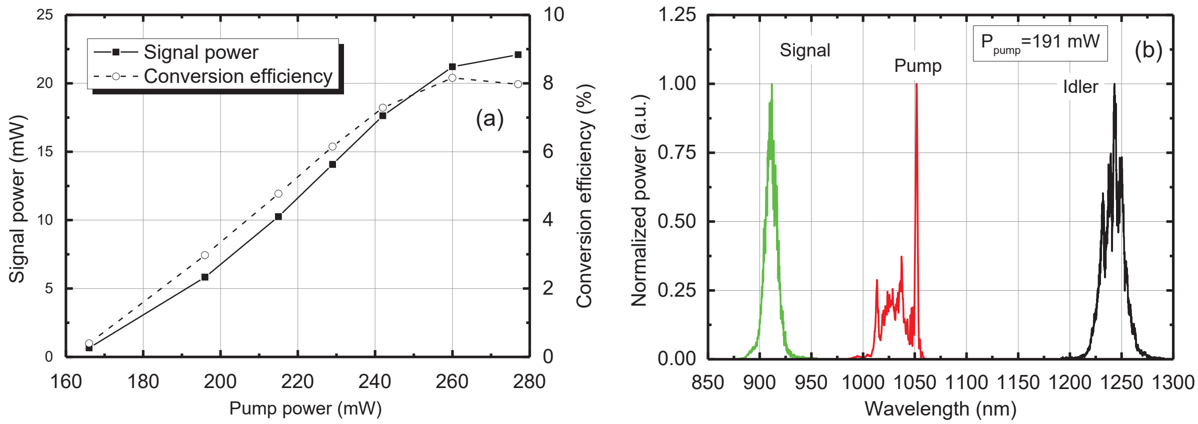

Figure 4. a) Measured signal average power and conversion efficiency versus pump average power at wavelength conversion stage; b) Normalized pump, signal and idler spectra at 191 mW pump average power at wavelength conversion stage.

Wavelength-converted pulses were directed to correlated photon generation stage through free space setup (see Figure 1), which was implemented to correct some of parameters of generated pulses. Short-pass filter was used to block pump and idler waves, and to transmit only signal wave. Polarizer and half-wave waveplate were used to clean polarization state and to align resulting polarization with orientation of PCF fiber used in correlated photon generation stage. Diffraction grating together with coupling to PCF fiber core were used to filter pulse spectrum. Final optimization of the system was carried by attempting to achieve FWM in classic manner (in correlated photon generation stage) by increasing energy of pump pulses. Spectrum measurements showed signs of signal wave generated at 921 nm and idler wave generated at 929 nm (Figure 5). Based on these spectral measurements, interference optical filters were aligned to separate spatially signal and idler waves.

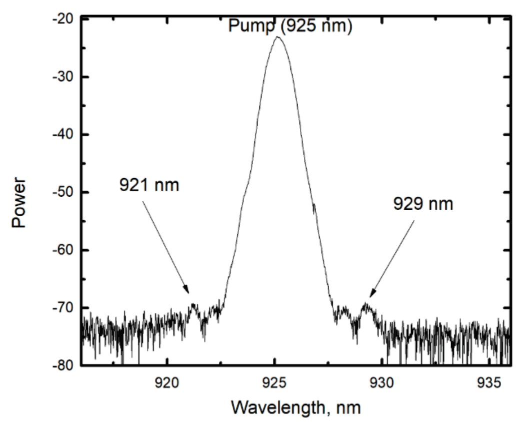

Figure 5. Measured spectrum at the output of the correlated photon generation stage at elevated pump pulse energy.

4. SINGLE-PHOTON GENERATION EXPERIMENTS

A beam splitter experiment (also called the Hanbury-Brown-Twiss experiment [14]) was carried to test whether single photons are generated by the source. For this test, a 50/50 beam splitter was inserted in the Idler channel (Figure 6). Outputs of the beam splitter were directed to single-photon detectors (Excelitas SPCM-850-43-BR1). Also, a InGaAs photodiode was used at synchronization channel output to register timing of the pump pulses.

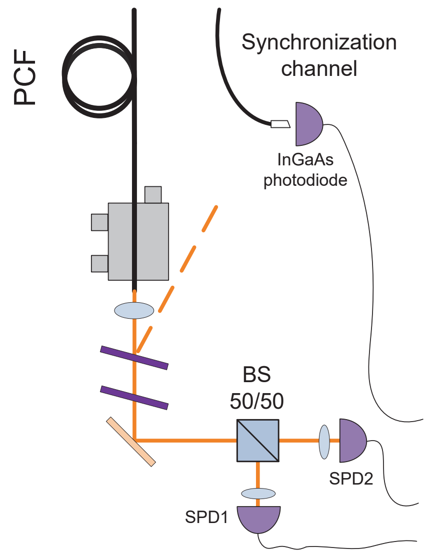

Figure 6. Schematic diagram of single-photon test setup. SPD1/2 – single-photon detector 1/2.

Outputs of two single-photon detectors and the photodiode were connected to 20 GHz bandwidth oscilloscope for data acquisition. Memory of the oscilloscope allowed to capture signal from all 3 channels for ~10 ms at sampling interval of 320 ps. Registered signals were then post-processed, double counts and single counts of detectors were evaluated. Pulses from synchronization channel were used as a gating signal, which allowed to eliminate "dark counts" registered in-between of pump pulses. As an illustration of registered signals, excerpt of registered waveforms is shown in Figure 7. In provided graph, black trace corresponds to synchronization pulses, red trace corresponds to pulses form single-photon detector 1, and blue trace corresponds to pulses from single-photon detector 2. In shown example, there is one single-count from detector 1 and two single-counts from detector 2. Also, a dark count pulse from detector 2 can be seen, which is discarded, because it does not overlap in time with synchronization pulses.

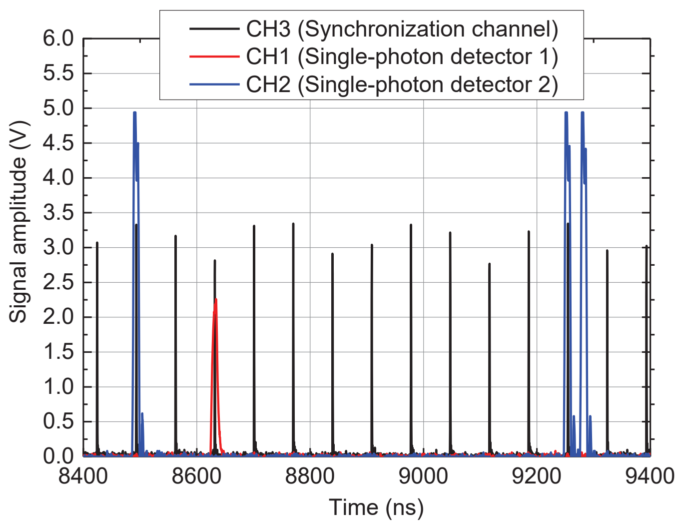

Figure 7. Excerpt of registered (raw) signal data from detectors.

Signal acquisitions from detectors at different pump power of main amplifier were registered and processed. In developed setup, pump power of fiber amplifier is the main easily controllable parameter allowing to optimize operation of the system. As expected, with reduction of pump power (pump laser diode (LD) current), single-count to double-count ratio improved indicating that source could be driven in single-photon per pulse regime. Results of this investigation is summarized in Figure 8.

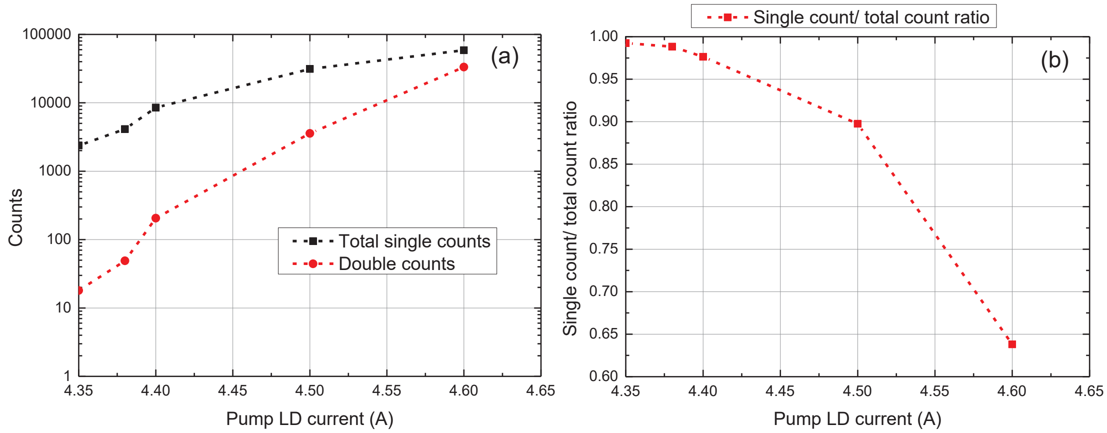

Figure 8. a) Total number of single counts (black points) and double counts (red points) per measurement window versus pump laser diode current of fiber amplifier stage; b) Single count to double count ratio versus pump laser diode current of fiber amplifier stage.

As can be seen from the graphs, with reduction of pump power, single-count to double-count ratio increased up to 99 %, indicating minimal multiphoton events. Detected single-photon rate at 4.35 A pump LD current was >230 000 photons/s (Fig. 9). If we account for detector efficiency of 49%, we can estimate that single photon rate directly from the source was >460 000 photons/s at 4.35 A LD current. With increase of pump LD current single photon generation rate increases but single-count to double-count ratio reduces and so fidelity of the generated photons deteriorates.

During experiments, electrical power consumption of the source was evaluated as well. At optimal operational conditions, power consumption of pulse generator and fiber amplifier was 2.3 W and 7 W, respectively. So total power consumption of the source was 9.3 W. This does not include possible power consumption required for cooling of the system because for the experiments convection cooling in laboratory environment was sufficient.

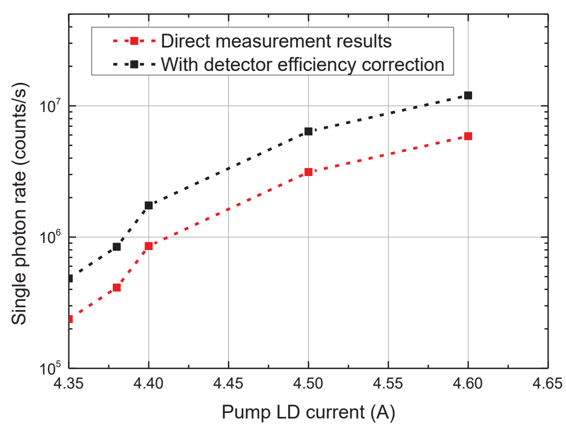

Figure 9. Measured single-photon rate versus pump laser diode current of fiber amplifier stage.

5. CONCLUSIONS AND FUTURE PERSPECTIVE

Optical fiber-based pulsed source of correlated photons was demonstrated experimentally. Operation of the source relies exclusively on intrinsic nonlinear properties of the fiber. Self-phase modulation effect is utilized in optical pulse generation stage, whereas four-wave mixing effect is used in wavelength conversion and correlated photon generation stages. Operation of the source was characterized by measuring single-photon generation rate and single-count to double-count ratio. Measurement results showed >460 000 photons/s single-photon generation rate at 99 % single-count to double-count ratio. Further investigation of the source capabilities is in progress. After receiving additional equipment, heralding properties between signal and idler channels will be characterized.

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