A microstructured fiber source of photon pairs at widely separated wavelengths

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OCIS codes: (270.5565), (190.4380), (060.5295).

Sources of photon pairs constitute a fundamental building block for most emerging quantum communication technologies. They are essential for the development of photonic quantum entanglement [1], which is required for most quantum communication tasks including Quantum Key Distribution (QKD) [2, 3], as well as quantum repeaters required to break the distance barrier of QKD [4]. High quality sources of photon pairs are also needed for Heralded Single Photon Sources (HSPSs) [5].

Photon pairs have been generated through various techniques including Spontaneous Parametric Downconversion (SPDC) in $\chi^{(2)}$ nonlinear crystals [6], atomic ensembles [7] and in quantum dots [8]. One drawback to these techniques is the limited coupling efficiency into optical fiber, which impacts on the performance of quantum communication schemes. To avoid this drawback, the generation of photon pairs directly inside optical fiber, through $\chi^{(3)}$ Spontaneous Four-Wave-Mixing (SFWM), has been studied [9–15].

Photon pairs at telecommunication wavelengths (1550 nm) have been generated in standard telecommunication Dispersion Shifted Fiber (DSF) by pumping in the anomalous dispersion regime [10]. In these experiments, the wavelengths of the generated photon pairs are close to the pump wavelength. More recently, photon pairs have been generated with visible and near-infrared wavelengths by pumping in the normal dispersion regime of novel Microstructured Fibers (MSFs) [11]. A seldom considered source is one that produces photon pairs with one photon in the visible and one photon at telecommunications wavelengths [12, 16]. Such a source is necessary to create entanglement for quantum repeaters that can link free-space networks, which generally rely on visible photons, with telecommunication networks, which depend on wavelengths near 1550 nm. In addition, a high-quality HSPS at telecommunication wavelength can be obtained with a heralding photon at 810 nm wavelength as high-efficiency detectors are available [17]. Also, as the wavelengths of both generated photons lie outside the spectral range of spontaneous Raman scattering of the pump photons, cooling the MSF to cryogenic temperatures, as in previous experiments [13, 14], is not required.

In this Letter we report on the generation of photon pairs with widely separated wavelengths with an MSF. We pumped an MSF, designed with a zero-dispersion wavelength of 1092 nm [18], with 1064 nm light and produced photons centered at 810 nm and 1548 nm.

![Figure 1. Phase-matching curves of the MSF [18]. The vertical line corresponds to the pump wavelength. Inset: Scanning Electron Microscope image of MSF.](image-url)
(see Fig 1). We confirmed the non-classical nature of the source by measuring classically forbidden values of the second-order auto-correlation function $g^{(2)}(0)$ of the 1548 nm photon field heralded by an 810 nm photon detection [15]. This important measure can be used to assess the visibility of two-photon interference [17,19] required for quantum repeaters as well as the security of QKD using an HSPS [20].

In our experiment (see Fig. 2) a mode-locked Nd:YAG laser pumped the 10 m MSF. The laser created 300-ps-long pulses at 1064 nm wavelength with a 100 MHz repetition rate and was spectrally purified by two transmission gratings. The wavelengths of the generated photons, 810 nm and 1548 nm, were verified using an optical spectrum analyzer. The photons were separated using a custom made dichroic mirror. Post-MSF filtering of the pump was accomplished with notch filters, multi-pass dichroic mirrors, edge-pass filters and a fiber Bragg grating. This resulted in > 210 dB isolation of the pump beam and only 7 dB and 6 dB loss to the collection fibers for the 810 nm and 1548 nm photons, resp. This included 40% coupling efficiency into each fiber. This could be improved by splicing the MSF directly to a standard fiber, where transmissions up to 95% with MSFs similar to ours have been reported [12], and doing the filtering in fiber. The 810 nm photons were detected by a Si based single-photon detector ($D_H$) while the 1548 nm photons were sent to single-photon detectors configured in a Hanbury Brown & Twiss (HBT) experimental setup [21]: two InGaAs based single-photon detectors ($D_A$ and $D_B$), which were activated only when $D_H$ detected an 810 nm photon (i.e. the 810 nm photon heralded the 1548 nm photon), preceded by a fiber 50/50 coupler. Detection signals were collected by a Time-to-Digital Converter (TDC) only when $D_H$ detected a photon and $D_A$ and $D_B$ were not within dead-time. The overall efficiency was 8% and 0.25% for 810 nm and 1548 nm respectively. Note that the 10% detection efficiency of $D_A$ and $D_B$ was a significant contribution to this loss.

First, we measured count rates on $D_H$ and coincidence count rates between $D_H$ and $D_A$ as a function of power. Both have a nearly perfect quadratic dependency, which is a signature of SFWM when the probability of producing multiple pairs is much less than the probability of producing one pair, $p_{\geq 2} \ll p_{1}$ (see Fig. 3 inset), although this does not demonstrate the nonclassical nature of the source.

We also examined the coincidence detection rate between $D_H$ and $D_A$ as a function of the time delay between a detection at $D_H$ and the activation time for $D_A$. At 20 mW average power (approximately 670 mW peak power), the maximum coincidence rate was 268 counts/s. Displacing the activation time for $D_A$ by integer multiples of the time between subsequent pump pulses produced an accidental coincidence detection rate of 14.6 counts/s (coincidence detection rates at non-integer multiples were negligible), resulting in a Coincidence-to-Accidental Ratio (CAR) of 268/14.6 ≈ 18.3 (In general, the CAR was between 20 and 10). Accidental coincidences were likely due to fluorescence from various optical elements.

To demonstrate the non-classical nature of the source, we measured the second-order auto-correlation coefficient at zero time-delay, $g^{(2)}(0)$, of the heralded photon field as a function of pump power. The $g^{(2)}(0)$ was calculated according to

$$g^{(2)}(0) = \frac{P_{AB|H}}{P_{A|H} \times P_{B|H}},$$

where $P_{AB|H}$ is the probability for a $D_A$ and $D_B$ coincidence detection, per pump pulse, provided there was a detection at $D_H$, and similarly for $P_{A|H}$ and $P_{B|H}$ [17,22].

Classical theory demands that $g^{(2)}(0) \geq 1$; uncorrelated detections yielding $g^{(2)}(0) = 1$ and photon bunching from a thermal source yielding $g^{(2)}(0) = 2$ [23]. The quantum description of light allows for $0 \leq g^{(2)}(0) < 1$: this is known as photon anti-bunching. In particular, a source that emits only one photon pair per pulse could produce $g^{(2)}(0) = 0$, if used in an heralding HBT experiment. However, this is not achievable with photon pairs generated from SFWM as there always exists a finite probability that the source emits multiple pairs per pump pulse, which raises $g^{(2)}(0)$ above zero. Nevertheless, measuring a $g^{(2)}(0) < 1$ confirms the nonclassical nature of the source, and consequently the possibility to use the source in quantum communication protocols.

The results of our $g^{(2)}(0)$ measurements are presented in Fig. 3. The $g^{(2)}(0)$ is well below one, and matches
well with theoretical predictions, over a wide range of pump powers. The theoretical curve was calculated using a method similar to [17]. A Poisson distribution was assumed for the number of photon pairs as the coherence time of the photon pairs (inferred from bandwidth measurements of 1.6 nm and 5.8 nm for the 810 nm and 1548 nm photons, respectively) was much shorter than the duration of the pump pulse [24]. The scatter in the points is mainly due to temperature instabilities in the laser cavity. These variations change the peak power of the laser, which affects the probability to produce a photon pair and thus the g(2)(0) detection as a function of power. The quadratic dependency is a characteristic of FWM when p ≥ 2 ≪ p1. This data was obtained from a different, yet typical, experimental run than the g(2)(0) data. (b) g(2)(n) at 12.5 mW average pump power (3.5 × 10^4 810 nm counts/sec resulting in 4.4×10^{-3} photon pairs per pulse), where n is the D_H detection offset between D_A and D_B activations.

Fig. 3(b) depicts g(2)(n) at 12.5 mW average pump power for various D_H detection offsets (n) between the activation of D_A and the activation of D_B (i.e. when D_H detected a photon D_A was activated such that it could detect the simultaneously created photon, while D_B was activated after n more D_H detections). One observes that g(2)(n) ≈ 1 for all n except n = 0. This is expected as photons produced by different laser pulses are uncorrelated. The sharp g(2)(n) decrease at n = 0 [g(2)(0) = 0.11±0.01, with p_{ABH} = (2.975±0.006)×10^{-3}, p_{B/H} = (3.162±0.006)×10^{-3} and p_{AB/H} = (1.05±0.11)×10^{-6}] is a demonstration of photon antibunching.

In conclusion, we have demonstrated an MSF source of photon pairs with widely separated wavelengths through measurements of the second-order auto-correlation function, which confirmed the nonclassical nature of the source. The source is compatible with existing telecommunication infrastructure and, moreover, can be developed into a source of quantum entanglement suitable for future experiments in quantum communication including quantum repeaters that can link free-space and fiber-based quantum channels into one coherent network.

Acknowledgements

The authors thank Mikaël Leduc and Vladimir Kiselev for their technical support, Yasaman Soudagar for many useful discussions and NSERC, iCORE, GDC, FEDER, CFI, AET, QuantumWorks, AIF, NATEQ, and CIPI.

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