Photon-pair source at 2090 nm for long-distance quantum communication

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Abstract. We report the generation of entangled photon pairs at 2,090 nm, as a basis for free-space quantum communication in an atmospheric window with low solar background. The source is based on spontaneous parametric down-conversion in periodically poled lithium niobate crystal delivering high coincidence-to-accidental ratio. We demonstrate the two-photon Hong-Ou-Mandel quantum interference and polarization entanglement.

Keywords: Quantum source, HOM interference, Ultrafast nonlinear optics

1 Introduction

The 2 μm spectral region is highly desirable for a broad range of photonics applications and is just recently starting to be explored. Above 2 μm lies an atmospheric transparency window with nearly one third of the solar blackbody radiation as what is typical at telecom wavelengths. There is, therefore, a growing interest to deliver sources and detectors operating in this wavelength range for free-space optical communications. This is highly desirable in quantum-secured links, such as for daylight satellite-to-ground and satellite-to-satellite based quantum communications [1, 2]. For instance, satellite-based quantum communication in daylight, recently shown with sources at telecom wavelengths (1550 nm) [2], could be improved when operating at 2 μm where the solar background is lower. Guided communication is also rapidly developing into the 2 μm region to satisfy the need for larger bandwidth to the increasing volumes of data traffic. Recently, guided wave optical communications based on Silicon-Germanium waveguide technology has been shown to reach 10 Gb/s transmission over a centimeter-long waveguide [3].

Within this context, we have investigated the generation of photon pairs at 2090 nm and we report the characterization of the production and detection efficiency achieved with the available technology. In addition, we have characterized the photon-pair source quality in terms of the coincidence-to-accidental ratio (CAR) and further demonstrated the photon-pair indistinguishability with a Hong-Ou-Mandel (HOM) measurement [4]. Finally, we have measured polarization entanglement.

2 Experiment and Results

Exciting a 1 mm long periodically poled magnesium-doped lithium niobate (MgO-PPLN) crystal (30.8 μm poling period, to be operated in a type-0, developed by Covesion Ltd.) with 1045 nm radiation delivered by a Chromacity Spark 1040 Ytterbium-laser (pulsed, 120 fs pulse duration, 80 MHz repetition rate), we induced spontaneous parametric down-conversion (SPDC). The crystal was temperature stabilized at 30$\pm$ 0.1 °C, to optimize the collinear generation of photon pairs at the degeneracy wavelength of 2090 nm. The signal and idler photons emitted by the multi-mode SPDC process were separated in the spatial far-field with a D-shaped mirror and directed towards the two fiber couplers. A graphical representation of the setup is shown in Figure 1.

A 10 mm thick germanium filter was placed in front of the source to act as a long-pass filter and to block photons below a wavelength 1.85 μm, rejecting residuals of the pump laser. Additional 50 nm wide bandpass filters were used in front of the fiber coupled detectors to select only the spectral component around degeneracy. First, the generated photon flux has been measured by phase-locked detection from an amplified InGaAs photodiode. The efficiency in the linear generation regime is of the order of $\eta = 10^{-10}$. The quantum efficiency of the superconducting nanowire single-photon detectors (SNSPD) mounted in a closed-cycle Gifford McMahon cryostat with an operating temperature of 2.5 K to be of

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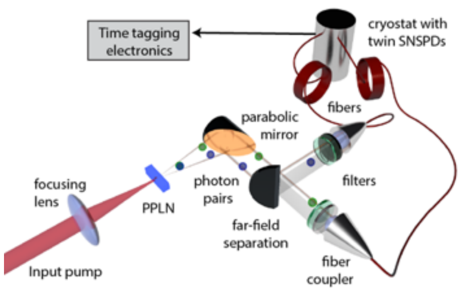

Figure 1: Experimental setup for the generation and detection of down-converted photon pairs at 2.08 μm.

the order of 10^{-2}. The coincidences were measured using a time-to-digital converter (HydraHarp 400).

Figure 2 shows the coincidence measurement, with a clear maximum at zero delay and residual peaks at time delays corresponding to the laser's repetition rate. These residual correlations emerged from down-conversion events in consecutive pulses, which constitute the background. Further accidental events occurred as a result of uncorrelated background photons and dark counts. We experimentally optimized the phase matching condition by maximizing the CAR. Figure 2 also details the variation of CAR as a function of input pump power to the crystal.

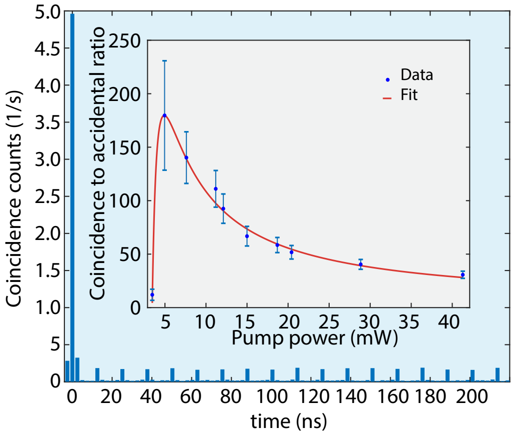

Figure 2: Coincidence counts for a 30 min integration time and CAR measurements. The red curve is a fit for the experimental data.

Finally, we observed the two-photon interference of generated photon pairs in a HOM scheme, with a visibility of 88.1% (without background correction), thus demonstrating the indistinguishability of the two photons. The experimental setup for measuring the HOM-dip is shown in Figure 3 and the result of HOM-dip is shown in Figure 4. The raw experimental data is fitted with an inverted sinc function weighted with a Gaussian.

For demonstrating polarization entanglement, we used a 0.3 mm thick MgO:PPLN type-II (e-oe) down conversion crystal with a poling period 13.4 μm at 110$\pm$ 0.1 °C. We performed the Bell-CHSH test and the Bell parameter was measured to be S=2.20$\pm$0.09 >2, clearly demonstrating polarization entanglement.

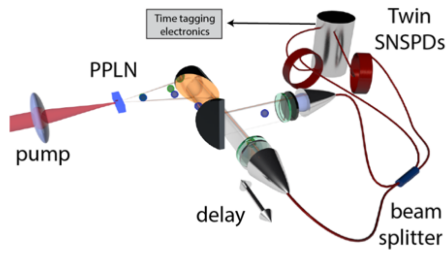

Figure 3: A polarization-maintaining-fiber-based 50:50 beam splitter is inserted in front of the coincidence detection together with a tuneable delay line allowing to adjust the temporal overlap of the down-converted photons at the beam splitter for the HOM interference.

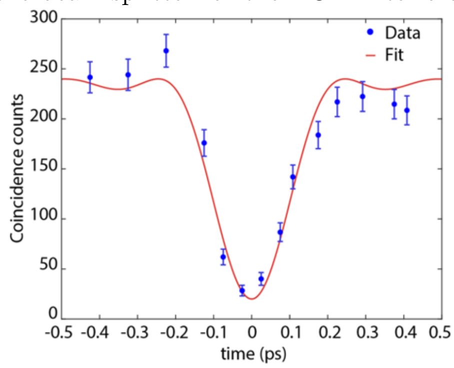

Figure 4: The observed two-photon interference (HOM dip) where dots represent the experimental coincidence counts, and solid curve is fit to the experimental data.

3 Conclusion

We have demonstrated an efficient quantum source in a free-space configuration at 2090 nm and verified the realization of indistinguishable photon pairs through two-photon interference. The HOM dip with high visibility proves that this source can be successfully used in applications requiring interferometric measurements. This work paves the way for technological applications for quantum sensing and secure long-distance quantum communications within this wavelength regime.

References

[1] H. Kaushal, and G. Kaddoum, Optical communication in space: Challenges and mitigation techniques, *IEEE Commun. Surv. Tutor*, 19:57, 2017.

[2] S.-K. Liao, et al., Satellite-relayed intercontinental quantum network, *Phys. Rev. Lett.*, 120:030501, 2018.

[3] M. Lamy, et al., Ten gigabit per second optical transmissions at 1.98 μm in centimetre-long SiGe waveguides, *Electron. Lett.*, 53:1213, 2017.

[4] C. K. Hong, Z. Y. Ou, and L. Mandel, Measurement of subpicosecond time intervals between two photons by interference, *Phys. Rev. Lett.*, 59:2044, 1987.