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A high-brightness source of polarization-entangled photons for applications in free-space

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***Abstract*—We have developed and engineered a simple, but highly efficient source of polarization-entangled photons, designed specifically for the distribution of entangled photons via long-distance, free-space links. The source is based on spontaneous parametric down-conversion (SPDC) from crossed periodically poled potassium titanyl phosphate crystals (PPKTP), pumped by a compact 405-nm laser diode. We detect 0.64 million photon pair events/s/mW, and achieve an overlap-fidelity with the maximally entangled Bell-state of 0.98.**

I. Introduction

The use of polarization-entangled photons is already essential for numerous quantum optics experiments, such as quantum teleportation [1], quantum cryptography [2], quantum dense coding [3], quantum enhanced metrological schemes [4], quantum computation [5] and quantum communication [6]. A commercial implementation of communication protocols utilizing entangled photons is possible in the foreseeable future and could play an important role in the enhanced communication protocols of the years to come. State-of-the-art laboratory sources of entangled photons are generally ill-suited for applications in harsh space environments, either owing to the use of bulky lasers, the requirement for active interferometric stabilization or insufficient photon-pair generation-efficiency to overcome the expected losses in long-distance free-space links. Thus, an integral milestone for the experimental implementation of such protocols over satellite-links [7], is the development of robust, space-proof sources of entangled photons with high brightness and entanglement visibility.

Within the ESA-funded EQUO project we have developed and engineered a high-brightness (pairs/s or bit-rate) and high-visibility (low quantum bit error ratio) source of polarization-entangled photons [8]. We generate polarization-entangled photon pairs via collinear, non-degenerate SPDC emission from two crossed type-0 PPKTP crystals, as previously demonstrated in [9] for beta-BaB_2O_4 crystals (BBO). The spectral characteristics of the generated photon pairs were chosen to maximize the detectable flux rate over long-distance atmospheric links. With envisioned applications in space, the source was designed to meet the added constraints of robustness and compactness; the hardware and driving electronics were fitted on a compact breadboard for its use in out-of-the lab experiments. We have also demonstrated that the source can be further integrated and is likely to become compliant with the severe requirements of space flight and operation.

II. Efficient pair-generation

To date the most commonly used process for the generation of polarization-entangled photon pairs is spontaneous parametric down-conversion (SPDC) in non-centro-symmetric second-order nonlinear crystals. In this process, mediated by the crystal nonlinearity $\chi^{(2)}$, a high energy pump photon ω_p decays into a pair lower energy photons, referred to as signal ω_s and idler ω_i photons. Due to the spontaneous nature of the process, this decay only occurs with a typical probability of 10^{-7}, whereby the crystals birefringence and dispersion, as well as the energy conservation

$$\omega_p = \omega_s + \omega_i \tag{1}$$

determine under which conditions this process may occur. The nonlinear crystal (BBO, KTP, LN) must be carefully tailored and tuned, such that the signal and idler fields interfere constructively with the pump along the propagation direction. In a photon picture this is nothing but the momentum conservation condition

$$\vec{k}_p = \vec{k}_s + \vec{k}_i \tag{2}$$

with the wave-vectors $\left|\vec{k}\right| = 2\pi\frac{n(\lambda)}{\lambda}$ of pump, signal and idler photons. This is commonly known as the phase-matching condition, and can be achieved using the birefringence of the nonlinear crystal to compensate for the phase-mismatch (by choosing the propagation direction and polarizations of the respective waves accordingly). A more recent development in nonlinear optics, known as quasi-phase-matching, allows the strict phase-matching condition for the collinear case to be modified by periodic inversion of the nonlinear coefficient, with a poling period Λ

$$\frac{1}{\Lambda} = \frac{n(\lambda_p)}{\lambda_p} - \frac{n(\lambda_s)}{\lambda_s} - \frac{n(\lambda_i)}{\lambda_i} \tag{3}$$

The additional degree of freedom introduced with the poling period significantly relaxes the requirements of phase-matching for type-0 (pump, signal and idler co-polarized), type-I (signal and idler co-polarized) or type-II (signal and idler orthogonally polarized) configurations, allowing quasi-phase matching at almost arbitrary wavelength combinations. Furthermore, periodic poling allows using materials with high nonlinear coefficients, such as the d_{33} coefficient of KTP [12], while choosing the propagation direction of the interacting fields to be along one of the crystals principal axes (non-critical configuration), thus eliminating birefringent walk-off. This allows the use of long crystals (long interaction region) and ensures large overlap of the interacting fields as well as efficient coupling to single-mode optical fibers.

III. The Entangled Photon Source

We generate co-polarized photon pairs using the highly efficient, collinear type-0 interaction in PPKTP pumped with a 405-nm diode laser. In this configuration quasi-phase-matching the non-degenerate signal and idler wavelengths of 783-nm and 832-nm requires a poling period of 3.415 μm. These center wavelengths in the near infrared (around 810-nm) were chosen to maximize the detectable flux-rate over long-distance atmospheric links, whereby a trade-off between available LD pump sources, single-photon detector efficiency and link attenuation was made.

A. Crossed-crystal scheme

We generate polarization entanglement in a crossed crystal configuration [10] as depicted in Fig. 1. In this scheme a 405-nm pump photon polarized diagonally

$$|D_{\lambda_p}\rangle = \frac{1}{\sqrt{2}}\left(|V_{\lambda_p}\rangle + |H_{\lambda_p}\rangle\right) \tag{4}$$

with respect to the crystallographic z-axis of two mutually orthogonally oriented ppKTP crystals placed in sequence. If

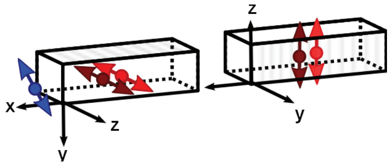

Fig. 1. Generation of polarization entanglement in a crossed crystal configuration. A diagonally polarized pump photon is equally likely to produce a photon pair in either the first or the second of two sequentially placed PPKTP crystals with their Z-axis oriented orthogonally with respect to each other. If the process is phase-coherent a plorization-entangled state is generated.

the pump is focussed to the center interface, the SPDC process is equally likely to occur in either the first crystal, resulting in the creation of a horizontally polarized photon-pair,

$$|H_{\lambda_p}\rangle \rightarrow |H_{\lambda_s} H_{\lambda_i}\rangle \tag{5}$$

or the second crystal, resulting in a vertically polarized pair.

$$|V_{\lambda_p}\rangle \rightarrow |V_{\lambda_s} V_{\lambda_i}\rangle \tag{6}$$

Since $|H_{\lambda_s} H_{\lambda_i}\rangle$ photon-pairs traverse the second crystal they acquire additional dispersion, compared to $|V_{\lambda_s} V_{\lambda_i}\rangle$ pairs. For a fixed phase-relationship to be maintained between the two emissions, a birefringent crystal with inverted dispersive characteristics must be placed in the SPDC path [11]. The process is thus made phase-coherent, and a polarization-entangled state with non-degenerate signal and idler wavelengths is generated.

$$|\Phi(\phi)\rangle = \frac{1}{\sqrt{2}}\left(|V_{\lambda_s} V_{\lambda_i}\rangle + e^{i\phi}|H_{\lambda_s} H_{\lambda_i}\rangle\right) \tag{7}$$

The non-degenerate wavelengths allow the photons to be separated by use of a wavelength division multiplexer (WDM) and the phase ϕ can be set by angle-tuning a birefringent plate placed in the SPDC path.

B. Experimental set-up

The experimental set-up is depicted in Fig. 2. The output of a 405.4-nm volume-holographic-grating stabilized LD is set to a diagonal polarization-state via a half-wave plate. The Gaussian pump-beam is then corrected for astigmatism via 2 cylindrical lenses and focused to an experimentally optimized waist size of approximately 17μm. The beam waist is located at the center interface of 2 crossed 20-mm PPKTP crystals placed on Peltier elements, that maintain the individual crystals at optimized phase-matching temperatures. The SPDC photons generated in the two crystals propagate co-linearly with the pump and inherit a waist of approximately 21μm. The SPDC is separated from the pump photons via an efficient dichroic mirror and traverses an Yttrium-Vanadat (YVO_4) compensation-crystal as well as a thin phase-plate that could be angle-tuned to set the phase of the state. The photons are then coupled into a single-mode fiber where the non-degenerate signal and idler photons are separated, using an in-fiber WDM. The output ports of the WDM were guided to two polarization analyzer modules (Alice and Bob), each consisting of a motorized polarizer and quarter-wave plate.

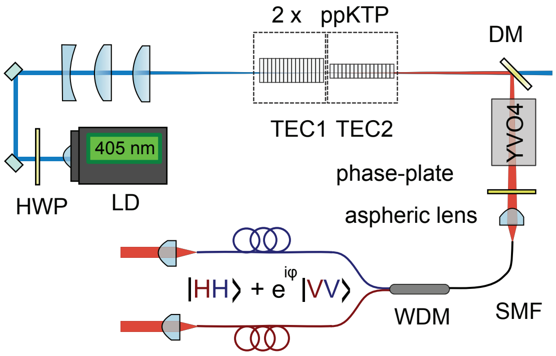

Fig. 2. Crossed-crystal source of polarization-entangled photons. For details, see text and reference [8].

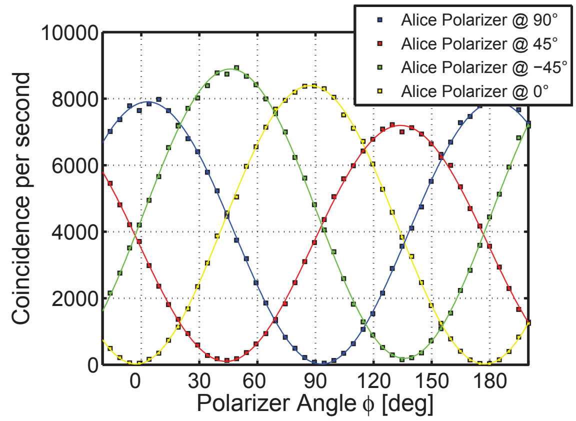

Fig. 3. Coincidence counts per second for varied polarizer angle in Bob's detector module. The visibility of the correlation functions obtained for diagonal D/A (red, green) and natural (yellow, blue) H/V measurement basis all exceeded 96%. (Square experimental data-points, line : best fit).

After the polarization analysis stage, long-pass and interference filters further filtered the SPDC photons from background emission and stray light. The photons were then detected via multi-mode fiber-coupled single-photon avalanche diodes (SPADs) with an approximate quantum efficiency of 40%. The photon-pair detection-events were then analyzed via a fast electronic AND gate, implemented in form of a fast time-to-amplitude converter (quTAU) with the coincidence window set to 2.4 ns. For a more detailed description of the experimental parameters, see reference [8].

IV. Results

Using the high nonlinearity of 20-mm long PPKTP crystals in an optimized focus geometry [13], [14], we achieved unprecedented normalized pair detection rates for this type of set-up. For photon pairs generated at the non-degenerate wavelengths of 780 nm and 840 nm, we detected 16000 photon pair events per second after a 3nm filter at a pump power of 0.025 mW. This corresponds to a record total number of 0.64 million photon pair detection-events per second / mW over a 2.3 nm bandwidth (spectral brightness of 0.28 Mcps/mW/nm). Scaling to the maximum pump power of 40 mW this results in a locally detectable coincidence rate of 20 Mcps, which would already require a total of 60 Si-SPADs for un-attenuated registration of such a number of pair coincidences (for details see [8]). The polarization-correlation functions, were assessed performing an angle-scan with the polarizer located in Bob's detector module, for several angle settings of Alice's polarizer. The coincidence counts show high-visibility fringes for all settings and depend only on the *relative* angle of the two polarizers (see Fig. 3); a unique feature of quantum entanglement. To fully characterize the quality of entanglement, we performed a quantum state tomography. For a pump power of 0.025 mW we measured an overlap-fidelity with the ideal $|\Phi_+\rangle$-state of 0.98.

A. Multiple-pair emission and visibility

At high pump powers, we observe an unavoidable reduction of the Bell-state fidelity and entanglement visibility. For the resulting high pair-generation rate, two or more photon pairs can be created within the timing window of the detection system. These multiple-pair emissions are uncorrelated from one another, since the timing window of the detection system (>1ns) is typically much larger than the coherence time of the SPDC (<1ps), thus reducing the effective quality of the entanglement. Generally, to operate in a useful limit of entanglement quality, the rate of double-pair emissions should be kept below 5% . This is typically achieved as long as the average emitted pair-number per coincidence-window t_c is lower than 0.1 ($R \times t_c < 0.1$, where R is photon-pair emission rate and t_c is the detector-characteristic timing-window). With our source we observe that, given the 2.4-ns coincidence window, the entanglement visibility drops to 80% at pump power of 2.2 mW. The key point to note is that, while higher pair rates are possible using higher pump powers, it is the accidental coincidences that determine the maximum pair generation rate for which high visibility is still achievable. This demonstrates that the use of higher photon pair numbers in SPDC will require further advances in detector technology.

V. Conclusion

We have designed, manufactured and tested a highly efficient source of polarization-entangled photons, exhibiting an unprecedented normalized pair detection rate of 0.64 Mcp/mW and a detected spectral brightness of 0.28 Mcp/mW/nm . Importantly for quantum-communication applications, the Bell-state fidelity reached a staggering value of 0.98. The compact footprint and simple design make the source an ideal device for field experiments and envisaged applications in space, as it is based on components suitable for future space qualification.

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