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Characterization of Entanglement Photons Generated by a Spontaneous Parametric Down-Conversion Pulse Source

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ABSTRACT

Quantum computation and quantum communication require sources of entangled photons, especially from low-cost diode lasers. This study considered a polarization entangled photons pulse source produced via a spontaneous parametric down-conversion process in the type-I phase-matching of two nonlinear crystals, incorporating a continuous wave laser diode operating in pulse mode as a pump. The generated photons were measured based on visibility as a function of the pump frequency and collection apertures. A polarization correlation between photon pairs of approximately 93% and a Bell parameter S value of 2.56 ± 0.05 were obtained using the source described here.

Keywords: entanglement, parametric down-conversion, Bell inequality, quantum communication

INTRODUCTION

Entangled photons are key elements in the field of quantum information and quantum communication and are required for methods like quantum teleportation and quantum dense coding, particularly quantum cryptography (Bouwmeester *et al.*, 2000). In addition, photon pairs are essential for recently proposed methods in quantum metrology (Castelletto *et al.*, 2004), and for many investigations of basic quantum effects. Historically, high-quality polarization-entangled states have been produced via the nonlinear process of spontaneous parametric down-conversion (SPDC) (Burnham and Weinberg, 1970), in which one high-energy pump photon splits into two lower energy daughter photons (called the signal and idler). Down-conversion can be realized in two ways: in type-I (type-II) phase-matching, an extraordinary polarized pump down-converts into two ordinary polarized photons (one ordinary polarized and one extraordinary polarized photon). Sources based on type-II phase-matching are dominant for ultrafast entanglement generation and are nevertheless limited by fundamentally small solid angles over which entanglement persists, or require interferometric configurations (Kwiat *et al.*, 1995; Kim *et al.*, 2003; Barbieri *et al.*, 2004; Shi and Tomita, 2004; Hodelin *et al.*, 2006; Kuzucu and Wong, 2008). In contrast, type-I entanglement sources are advantageous because of their comparatively high brightness, stability and ease-of-alignment (Kwiat *et al.*, 1999). Nevertheless, traditionally, such sources have been limited by reduced entanglement with larger collection irises and increasing pump bandwidths. Recently, ultra-bright type-I sources of entangled photons which combine multiple decoherence-compensation techniques have been developed (Rangarajan *et al.*, 2009). This paper describes the

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preparation of a Bell state, relying on non-collinear, two-crystal scheme type-I phase-matching pumped by the pulse beam of a violet diode laser. The created photons are characterized in terms of the frequency of pump beam collection efficiency. The polarization correlation between photon pairs is verified experimentally by violation of the Bell inequality in the Clauser-Horne-Shimony-Holt (CHSH) version (Clauser *et al.*, 1969).

MATERIALS AND METHODS

A schematic diagram of the experimental layout to produce polarization-entangled photons is shown in Figure 1. A continuous wave (cw) diode laser (Newport model LQA-405E) operating in pulse mode was used to produce a pulse beam of 60 mW, 50 kHz, 405-nm (specified by the manufacturer). The beam of photons passed through a blue filter, a linear polarizer, and a zero order wave plate before reaching a pair of beta barium borate (BBO) crystals. A detailed description of a two-crystal geometry is given in Kwiat *et al.* (1999). In brief, two adjacent thin nonlinear crystals were oriented orthogonally, such that a vertically V (horizontally H) photon in the polarized pump photon can down-convert into a pair of horizontally (vertically) polarized photons in the first (second) crystal (Figure 2).

If the pump beam is vertically (horizontally) polarized, down-conversion occurs only in crystal 1 (crystal 2). When the pump polarization is set to 45°, it can equally down-convert either crystal. The BBO are 5.0 × 5.0 × 0.5 mm, and in contact face-to-face, with the optic axis cut at 29.2°. For this cut, the degenerate-frequency photons at 810 nm are likely to be emitted in a collinear cone. For the data presented here, the crystal was tuned to emit into a cone with halt-opening angle 3°. The down-converted photons produced in the BBO crystals travel about 1 m before passing an adjustable iris diaphragm, a near-infrared polarizer, and an RG780 colored

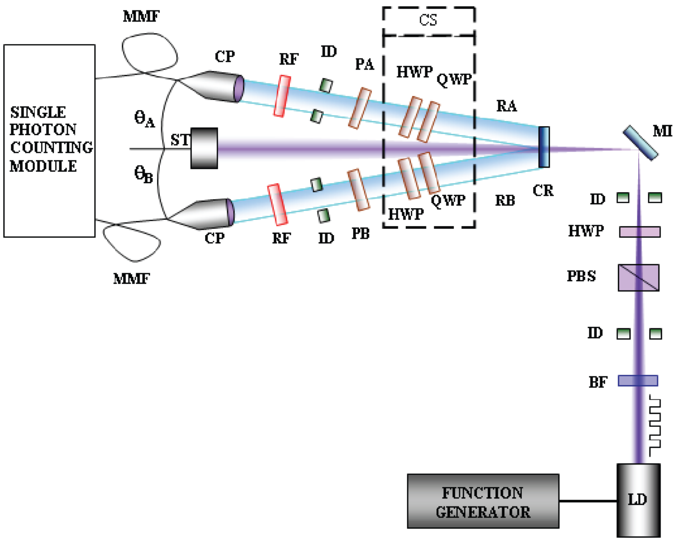

Figure 1 Schematic diagram of experimental layout. LD = laser diode module; BF = blue filter; ID = iris diaphragm; PBS = polarizing-beam splitter; HWP = half-wave plate; MI = mirror; CR = down-conversion crystals; RA = rail A; RB = rail B; QWP = quarter-wave plate; PA = polarizer A; PB = polarizer B; RF = red filter; CP = collimator; MMF = multimode fiber; ST = beam stop.

glass filter before being collected by fiber collimators into multimode fibers, which direct the photons to the commercial silicon APD single-photon detectors (Perkin-Elmer model SPCM-AQ4C). Coincidence counting is carried out using the coincidence circuit described in Dehlinger and Mitchell (2002). The down-converted photons emerge in a maximally entangled state (Equation 1):

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|H\rangle - e^{i\phi}|V\rangle|V\rangle\right) \quad (1)$$

where: $|H\rangle$ and $|V\rangle$ and are horizontal and vertical linear polarization states of the photon.

The relative phase ϕ in Equation 1 is determined by phase-matching constraints and depends on various parameters, such as crystal type and length, and the pump (down-conversion) frequency and momentum vector.

RESULTS AND DISSCUSION

To characterize the source, the visibility was measured as functions of the operating frequency of the laser diode and the size of the iris diaphragms. Opening these diaphragms increases the collection efficiency. Figure 3 shows that the highest visibility for H/V and a ±45° basis

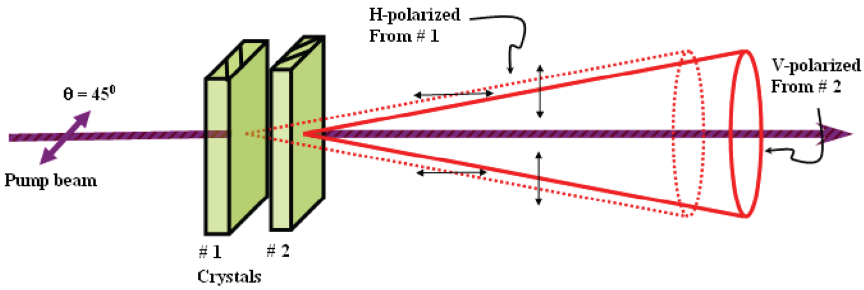

Figure 2 Two-crystal down-conversion source, not to scale. The crystals are 0.5 mm thick and in contact face-to-face, while the pump beam is approximately 1 mm in diameter. Thus, the cones of down-converted light from the two crystals overlap almost completely.

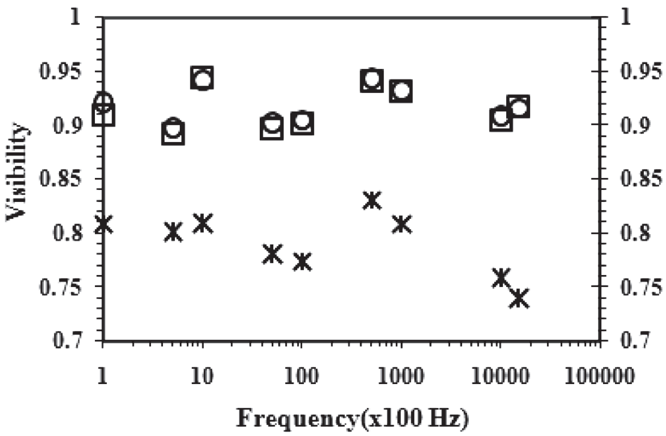

Figure 3 Plot of visibility versus frequency of the pump. The visibility for horizontal polarization (circles) is equal to the visibility for vertical polarization (squares), which is higher than the visibility for 45°(asterisks).

of approximately 95% and approximately 83%, respectively, with an input frequency of 50 kHz. Figure 4 illustrates clearly that for larger aperture sizes, the visibility is reduced. This reduction occurred because the ability to distinguish spatial and spectral changes was no longer fully maintained. Figure 4 also shows the detected coincidence rate as a function of the aperture size. The highest visibility level of 96% was obtained with a 10-mm aperture and an input frequency of 50 kHz.

Figure 5 shows the coincidence counts for the state $|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle|H\rangle - |V\rangle|V\rangle)$ and their sinusoidal fits. The polarization analyzer in path A was fixed at 45°, 90° and the analyzer rotated in

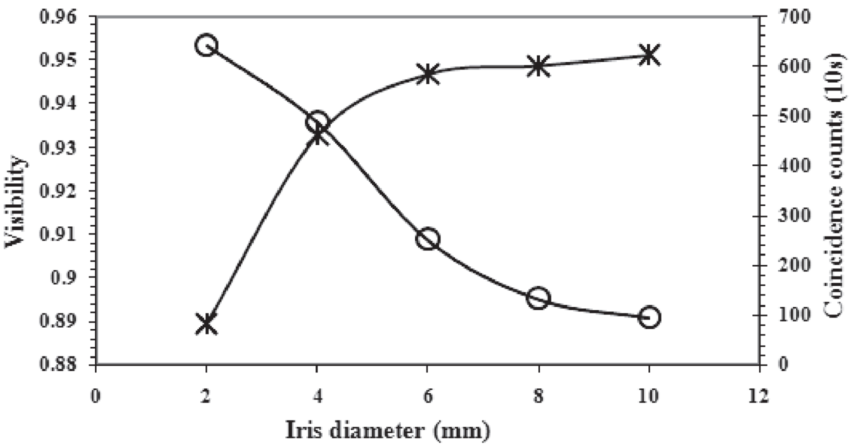

Figure 4 Plot of the fringe visibility (circles, left axis) and coincidence counts (asterisks, right axis) versus collection aperture sizes.

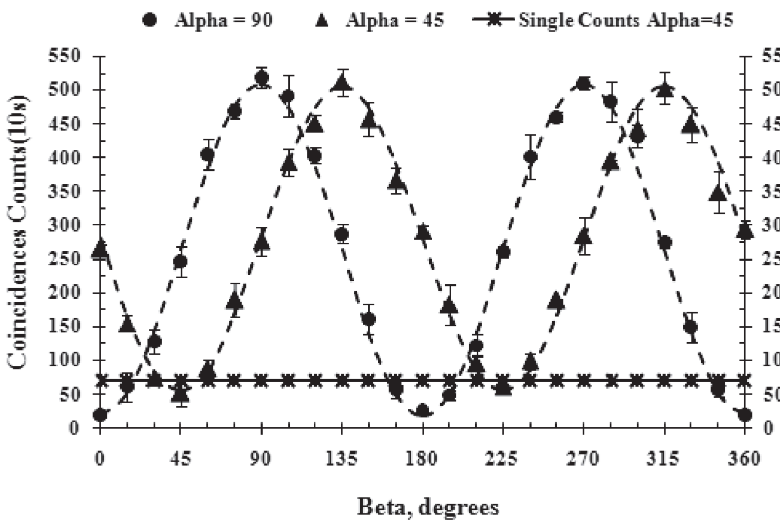

Figure 5 Plot of single counts (asterisks) and coincidence counts (mean ± standard error) for 45° (triangles) and for 90° (circles). Each data point was averaged three times over 10 s counting interval and the sinusoidal fits (dashed lines) were used for obtaining visibility and the S parameter in the CHSH inequality.

path B. Visibility levels were observed of V_{45} = 80.4% and V_{90} = 93.2%, with constant single counts of approximately 0.5%. Bell's inequality S value was -2.56 ± 0.05, which clearly violated the classical value of 2.

CONCLUSION

A potential scheme was presented for the generation of pulse polarization entangled photons from spontaneous parametric down-conversion in a two-crystal geometry. Polarization entanglement of the created photon pairs was demonstrated through violation of the Clauser Horne Shimony Holt (CHSH)-Bell inequality.

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