

Ultrabright femtosecond source of biphotons based on a spatial mode inverter

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A method of enhancing the efficiency of entangled biphoton sources based on a type II femtosecond spontaneous parametric downconversion (SPDC) process is proposed and implemented experimentally. Enhancement is obtained by mode inversion of one of the SPDC output beams, which allows the beams to overlap completely, thus maximizing the number of SPDC photon pairs with optimum spatiotemporal overlap. By use of this method, biphoton count rates as high as 16 kHz from a single 0.5-mm-long β -barium borate crystal pumped by second-harmonic radiation from a Ti:sapphire laser were obtained. © 2005 Optical Society of America

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Study of the entangled states of photons forms the basis of several emerging research fields, such as quantum information processing¹ and quantum lithography.² Further progress in these fields depends on the availability of an efficient method of obtaining entangled photon pairs. Currently the easiest way to obtain correlated photon pairs is via nonlinear spontaneous parametric downconversion (SPDC), in which a higher-energy pump photon is converted into a correlated pair of lower-energy signal and idler photons. By using these photon pairs and a nonpolarizing beam splitter (NPBS), one can prepare path-entangled biphoton states.³ It is convenient to characterize the efficiency (or brightness) of a biphoton source in terms of its pair flux and by the visibility parameter of its nonclassical interference.⁴ The brightness of SPDC-based sources depends on the parameters of the pump radiation, on the kind of nonlinear interaction, and on the geometry of the optical scheme used. Many reported studies have aimed at increasing the efficiency of SPDC-based entangled photon sources. For example, a polarization-entangled photon-pair yield as high as $46,000 \text{ s}^{-1}$ was obtained by use of periodically poled nonlinear crystals,^{5,6} by employing a two-crystal geometry,^{7,8} or by use of an optical cavity.⁹ Here we demonstrate a method with which one can obtain large biphoton yields from a single bulk optical nonlinear crystal.

According to the single-mode theory, where simultaneously only one photon arrives at each input of a lossless 50/50 beam splitter (BS), the probability of finding one photon in each output arm is zero.³ Therefore one can prepare the path-entangled biphoton state $|\psi\rangle = |2\rangle_1|0\rangle_2 + |0\rangle_1|2\rangle_2$ by use of a BS. The subscripts denote the output paths of the BS. Hence the SPDC is a convenient source of photons, where the photons of each pair are correlated by their birth time and can produce a biphoton state when combined in a BS.

The principle of the proposed method is illustrated schematically in Fig. 1. Type II degenerate SPDC in a β -barium borate (BBO) crystal produces orthogonally polarized, diverging ringlike signal and idler radiation cones. The SPDC process satisfies phase-matching conditions $\omega_p = \omega_s + \omega_i$ and

$\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$, where indices p , s , and i refer to pump, signal, and idler photons, respectively. Since the correlated photons are phase matched, their wave vectors $\mathbf{k}_{s,i}$ are located on the opposite sides of the SPDC cones with respect to the direction of the pump beam, as shown in Fig. 1(a). The key idea of this work is that if one could completely overlap the ringlike signal and idler cones, simultaneously ensuring phase matching between the paired photons across their entire area, the flux of biphotons would be enhanced toward the theoretical limit defined by the total flux of the SPDC photon pairs. Under the circumstances shown in Fig. 1(a), it is impossible to straightforwardly project the two rings onto each other. However, this restriction can be lifted by inverting one of the rings with respect to its geometric center, as shown in Fig. 1(b). Now signal and idler photons of the same pair occupy identical positions in their respective rings, and straightforward overlap of the rings produces detailed spatial overlap between all birth-paired photons. From them, entangled biphoton states can be constructed with the BS.

We tested these ideas using the setup illustrated in Fig. 2(a). The output of a femtosecond Ti:sapphire laser (Tsunami, Spectra-Physics, pulse length ≈ 100 fs, central wavelength 800 nm, repetition frequency 80 MHz) was frequency doubled (wavelength 400 nm,

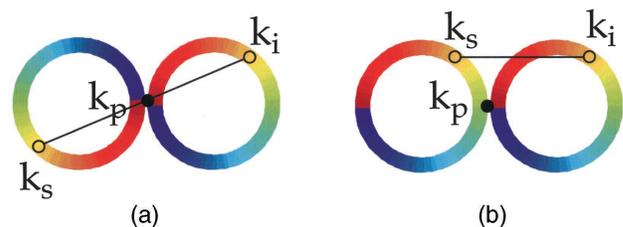


Fig. 1. (a) Schematic view of the two SPDC radiation rings seen along the direction of the pump beam (the solid dot located between the rings), when the pump beam (with wave vectors \mathbf{k}_p) propagates along the optical axis of the BBO crystal. The areas of the rings into which the birth-paired, phase-matched signal and idler photons (with wave vectors \mathbf{k}_s and \mathbf{k}_i) are emitted are marked by the same color. (b) Same view after signal mode inversion.

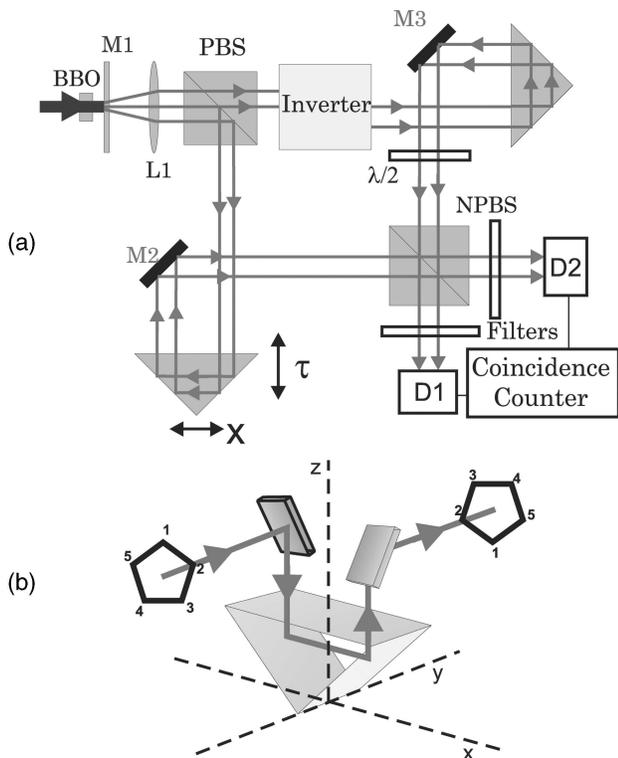


Fig. 2. (a) Experimental setup (see comments in the text), (b) schematic layout of the mode inverter.

average power ~ 115 mW) and used as a pump for the SPDC in a 0.5-mm-long BBO crystal. An extraordinary (*e*) signal beam and an ordinary (*o*) idler beam generated at 800-nm wavelength had spatial modes that showed diverging ringlike transverse profiles. Their centers were located on the normal to the plane of the drawing. After the BBO crystal the pump beam was largely rejected by dielectric mirror M1, which was highly reflective at the pump wavelength but transparent at the signal and idler wavelengths. The residual pump was blocked by long-pass filters. The signal and idler beams passed through mirror M1 and collimating lens L and were separated by a polarizing beam splitter (PBS). The beam transmitted through the polarizing beam splitter was then passed through the mode inverter (to be discussed below), which inverted its spatial mode as shown in Fig. 1(c), and as a result the \mathbf{k} vectors of both SPDC output beams were almost identically distributed across their profiles. The polarizations of both beams were set parallel by a $\lambda/2$ wave plate.

The mode inverter is illustrated in Fig. 2(b). It consists of two planar mirrors and a right-angle prism. Mode inversion is illustrated by the example of a pentagon image. On transmission through the mode inverter, each of the pentagon's numbered corners will undergo 180° azimuthal rotation about the geometric center. The same result is also achieved for arbitrary images.

After these transformations, two identical, collinearly polarized ringlike signal and idler beams were obtained. Subsequently, they were overlapped

on a NPBS [see Fig. 2(a)]. Their relative phase was varied by adjusting the mutual optical delay τ . In the two output arms of the NPBS, the transmitted-reflected photons were filtered spectrally by interference filters of 10-nm (FWHM) bandwidth and recorded by photodiodes D1 and D2 (SPCM-AQR-14, Perkin Elmer) connected to a single-photon counting unit (SR400, Stanford Research Systems) that allowed coincidence counting (CC) within a 5-ns temporal window. The effective transmittance of all filters was 0.35. All together, this setup allowed us to perform a standard Hong-Ou-Mandel test of the biphoton states,⁴ which is based on analysis of the CC rates as a function of optical delay.

The spatial overlap between the two beams was maximized by use of a CCD camera mounted in place of one of the detectors and monitoring of the rings. The initial overlap between the signal-idler rings was checked by blocking their top-bottom and left-right halves and merging them into a single ring. The final transverse alignment was achieved by optimization of the visibility of the quantum interference dip. Figure 3(a) illustrates various stages of the adjustment (from left to right). The first image shows two initial nonoverlapping rings obtained immediately after the BBO crystal. The second image, taken after the NPBS, shows the intermediate stage, where the two rings overlap partially. Since one beam has undergone mode inversion, photons belonging to the intersections of the two rings are uncorrelated. The last image shows fully overlapped rings, which are expected to yield correlated photon pairs across their entire area. The azimuthal alignment was checked by verifying the overlap between the bright spots of the residual pump beam on each ring. Unfortunately, the optical layout of the inverter does not allow

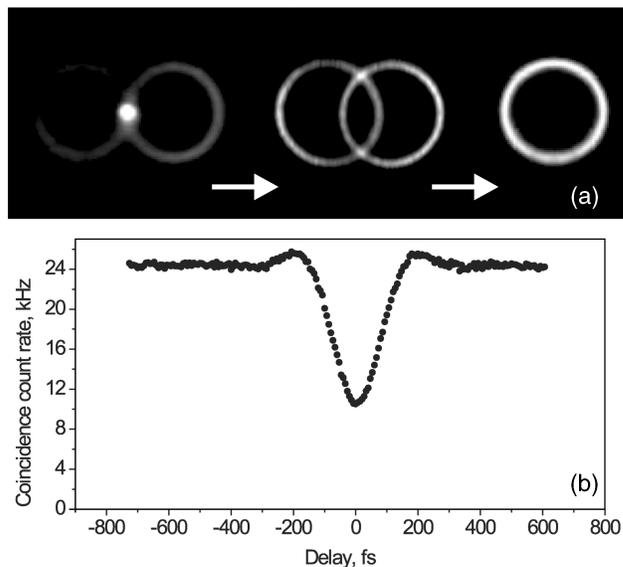


Fig. 3. (a) Images of signal and idler radiation rings taken by the CCD camera during various stages of alignment (from left to right: nonoverlapped, partially overlapped, and fully overlapped rings). (b) CC rate versus delay τ , measured when the two rings fully overlapped, as shown in the rightmost image in (a).

smooth, controllable rotation of patterns, which would help further to optimize the overlap.

Before the CC measurements, the single-photon character of the source was verified. An arbitrary delay, $\tau \neq 0$, was set between the signal and the idler beams. Single-count (SC) and CC rates were measured separately for the signal and idler beams. For both beams, SC rates of ≈ 500 kHz were found on each detector, while their accidental CC rate was 3 kHz (therefore all subsequent CC measurements were corrected by subtracting the 6-kHz background). However, when both beams were incident on the NPBS, the uncorrected CC rate increased to 30 kHz, thus indicating a low probability of pulse splitting on the NPBS when only one beam is present. This is possible when each pulse comprises only a few photons.

Figure 3(b) shows the CC rate versus the delay time between the two beams. The delay sets the time difference between the arrival of the birth-paired photons at the NPBS. For delays exceeding the inverse bandwidth of the interference filter (>200 fs), a CC rate of 24 kHz was observed. The dip in the CC rate observed at ($\tau = 0$) corroborates formation of the biphoton states. Without inversion of one of the SPDC rings the CC dip was not detected. The efficiency (visibility) of the biphoton source is only 42%; however, the total detected biphoton rate deduced from the bottom of the CC dip exceeds 16 kHz. Despite the low visibility, it is clear that the source proposed here can provide much higher biphoton flux than can a scheme that utilizes photons emitted along the selected directions. This result not only signifies effective overall overlap between the two rings on the NPBS but also shows that a high degree of overlap between the birth-paired photons was achieved. The total biphoton count produced by our setup is at least 100 times higher than that of a beamlike type II BBO-based scheme¹⁰ and at least 30 times higher than with a type I BBO-based setup.¹¹ The SC detection probability is proportional to the intensity of light incident on each detector and to the detector's efficiency. The CC detection probability is a product of SC probabilities. Given that the total transmission of our optical setup was 0.35, the efficiency of detectors was 0.65, and their dead time was 40 ns (every sixth laser pulse was registered), we can estimate the total $(16 \text{ kHz}) / (0.35 \times 0.65)^2 \times 6 \approx 1.7 \times 10^6 \text{ s}^{-1}$ biphoton flux. The maximum possible biphoton flux can be deduced from the maximum SPDC photon flux. For weak gain, $\approx 2.7 \times 10^7 \text{ s}^{-1}$ photon flux in each beam can be estimated from expressions given in Ref. 12. Hence the detected photon flux should be $27 \text{ MHz} \times 0.35 \times 0.65 \times 6^{-1} \approx 1 \text{ MHz}$, which is close to the measured signal SC rate of the signal (idler) beam. Consequently, the efficiency of our device is $1.7 \text{ MHz} / 27 \text{ MHz} \times 100\% \approx 7\%$. Although

theoretically all SPDC photons can be utilized for biphoton generation, such efficiency was not achieved because of practical limitations. In particular, because of the finite size of the SPDC emission spot we have not been able to collimate the signal and idler beams perfectly. This and other imperfections (e.g., azimuthal mismatch) of the setup need to be minimized further. Accurate estimation of the maximum practically achievable efficiency of the proposed source will require separate analysis.

In conclusion, we have demonstrated that the efficiency of entangled biphoton sources based on type II SPDC can be significantly enhanced by use of inversion of the spatial mode of one (signal or idler) SPDC beam. In principle, the inversion allows spatial overlap between the entire SPDC beams, and in particular between all the birth-paired SPDC photons. This is in contrast with widely used optical schemes in which only a small fraction of the total SPDC output is utilized. The high rate of the proposed biphoton source was confirmed experimentally by coincidence count rates as high as tens of kilohertz, obtained with femtosecond pumping of a single BBO crystal. We believe that the visibility of the source can be improved by the use of more accurate and more functional mode inverter schemes than that employed in our work. The present scheme can be improved too, for example, by replacing all the prisms by mirrors. In the future the proposed source of entangled biphotons may provide the seed for subsequent amplification steps that should help to increase further the biphoton yield.

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