Quantum interference with beamlike type-II spontaneous parametric down-conversion

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Abstract: We implement experimentally a method to generate photon-number−path and polarization entangled photon pairs using "beamlike" type-II spontaneous parametric down-conversion (SPDC), in which the signal-idler photon pairs are emitted as two separate circular beams with small emission angles rather than as two diverging cones.

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Since late 1980's, spontaneous parametric down-conversion (SPDC) has served as a good source of correlated or entangled photon pairs. In type-I SPDC, photons appear as a concentric ring centered at the pump beam due to energy and momentum conservation conditions and the pair photons are selected with a set of small apertures which are positioned at two conjugate regions on the concentric ring. In type-II SPDC, two such rings appear as the photon pairs are orthogonally polarized (one ring for each polarization). Depending on whether the orthogonally polarized photon pairs propagate collinearly or non-collinearly, one or two apertures are used to select correlated photon pairs, respectively. In any case, only a small fraction of emitted photons can actually be collected and, in general, the bigger the collection aperture, the less the measured correlation. This is due to the fact that, with bigger opening of the collection apertures, there are more probability of detecting un-correlated photons.

Recently, beamlike type-II SPDC was reported in literature [1, 2]. In beamlike type-II SPDC, the signal-idler photon pairs are emitted as two separate circular beams rather than as two diverging cones. Each beam has a Gaussian-like intensity distribution with a small divergence angle [1]. The immediate advantage of beamlike type-II SPDC over usual type-I and type-II SPDC, in which small apertures are required to define conjugate spatial modes, is that nearly all emitted photons may be collected in principle (without compromising two well-defined spatial modes). As a result, beamlike type-II SPDC exhibits better pair detection efficiency than usual type-I and type-II SPDC [1].

In this paper, we report a quantum interference experiment using beamlike type-II SPDC. Specifically, we report generation of the photon-number−path entangled state and the polarization-entangled state with beamlike type-II SPDC in one experimental setup.

Let us first briefly discuss how beamlike type-II SPDC can be generated. For a β-BaB_2O_4 (BBO) crystal, collinear degenerate type-II phase matching occurs when the pump beam (assumed 351.1 nm) and the optic axis of the crystal make an angle of $\theta_p = 49.2°$ inside the crystal. At this angle, the signal photon and the idler photon both are centered at 702.2 nm and the two emission cones or rings, shown as two dashed rings in Fig. 1(a), touch each other at the pump beam. The entangled photon pairs therefore propagate collinearly with the pump beam.

In the case of beamlike type-II SPDC ($\theta_p \approx 48.3°$), the tuning curve for both the e-ray and the o-ray are tangential to the 702.2 nm line as shown in Fig. 1(b). The signal and the idler photons are therefore emitted as two separate "beams", shown as two signal and idler "blobs" in Fig. 1(a), rather than two cones. Note that the signal-idler emission angles in beamlike type-II SPDC are fixed (in this case $\approx \pm 3.5°$) for a given pump and the SPDC wavaelengths. This is different from usual non-collinear type-II SPDC in which the signal-idler propagation angle may be easily adjusted by tilting the crystal in the optic axis plane.

The outline of the experimental setup can be found in Ref. [3]. A 1 mm thick type-II BBO crystal (cut at $\theta_p = 49.2°$) was pumped with a 351.1 nm (horizontally polarized) argon ion laser beam. The optic axis of the crystal lied in the horizontal plane so that both the signal and the idler photons propagated parallel to the surface of the optic table. The e-ray (o-ray) was therefore horizontally (vertically) polarized. A set of

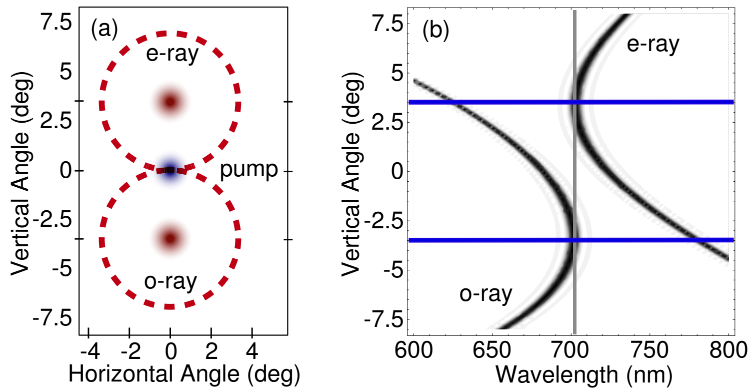

Fig. 1. (a) Two dashed lines show the emission pattern for the type-II collinear SPDC. For "beamlike" type-II SPDC, signal and idler photons are emitted as two separate circular beams showns as two "blobs" which are shown at the center of the collinear type-II SPDC emission cones. The optic axis is assumed to lie in the vertical plane and the vertical and the horizontal angles are the photon emission angles projected onto y and x axes, respectively. (b) Calculated tuning curve for beamlike type-II SPDC at 702 nm ($\theta_p \approx 48.3°$).

irises placed at $\pm 3.5°$ about 80 cm from the crystal helps tuning of the crystal angle for beamlike type-II SPDC generation.

Similarly to the results reported in Ref. [1], the ratio of the coincidence-count rate to the single-count rate was approximately $11.5\% \sim 12\%$ when the irises were about $5 \sim 7$ mm in diameter. When the pump beam was slightly focused with a 1 m focal lens (located about 1 m from the detectors), the ratio rose up to $\sim 15\%$ for similar size irises. Experimentally, this ratio is mostly limited by the detector efficiency (EG&G SPCM, typically 70% at this wavelength), the fiber coupler efficiency (about 65%, measured with a He-Ne laser), the filter transmission (approximately 55% peak transmission), and other small optical losses. The filter transmission, therefore, is the biggest factor for the coincidence/signal ratio and it may be improved by using better designed filters and by using a thicker BBO crystal which reduces the spectral bandwidth of SPDC. Note that, if the mode-matching technique described in Ref. [4] is used with the beamlike type-II SPDC, a much improved coincidence/single ratio (in turn better pair detection efficiency) may be possible.

The interferometer, which is used to generate polarization entangled states, for beamlike type-II SPDC consists of a half-wave plate and a 50/50 beamsplitter [3]. The horizontally polarized signal beam passed through a half-wave plate (HWP) and the signal beam and the idler beam were overlapped at the beamsplitter (BS). The delay τ between the two arms was adjusted with a computer controlled trombone prism. At each output ports of the beamsplitter, a polarization analyzer (A1 or A2), a spectral filter (F1 or F2), an iris, and a fiber-coupled single-photon detector were placed. The experimental data show that high-quality polarization entangled states can be generatedfrom beamlike type-II SPDC.

More details on beamlike type-II SPDC (advantages/disadvantages) will be discussed and spectral measurement as well as other interference measurement data will be presented.

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