Quantum Airy photons

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Abstract

With exotic propagation properties, optical Airy beams have been well studied for innovative applications in communications, biomedical imaging, micromachining, and so on. Here we extend those studies to the quantum domain, creating quantum correlated photons in finite-energy Airy transverse modes via spontaneous parametric down conversion and subsequential two-photon coincidence measurements, we verify their Airy spatial wavefunctions, propagation along a parabolic trajectory, and that the spatial modulation does not introduce any observable degradation of quantum correlation between the photons. These results suggest the feasibility of using spatially structured photons for practically advantageous quantum applications.

Keywords: quantum optics, quantum correlation, spatially structured light

(Some figures may appear in colour only in the online journal)

1. Introduction

There has been growing interest in surpassing the diffraction limit of light beams [1, 2] while engineering their directionality for the advanced imaging and remote sensing of chemical and biological agents [3–5]. In this pursuit, Airy wave packets have arisen as a unique and promising candidate for their non-diffracting propagation along parabolic trajectories that mimic free acceleration [6]. This extraordinary phenomenon was observed recently using finite-energy optical Airy beams, together with self healing where their spatial modes are automatically reconstructed after being partially blocked [7–9].

Thus far, optical Airy beams have been explored for exotic applications [10, 11] such as micro-particle manipulation [12, 13], surface plasmonic bending [14, 15], direction filamentation [16, 17], parabolic plasma channeling [18], micromachining along a curve [19], and superresolution imaging [20]. More recently, Airy beams have been exploited in optical parametric oscillators [21] and four-wave mixing in atomic vapor cells [22], with growing applications in medical science [23], defense [24], and optical communications [25, 26].

In parallel to these exciting studies in the classical domain, there has been accelerating progress in developing novel optical techniques harnessing the quantum-mechanical properties of photonic signals, where unprecedented capabilities are promised for remote sensing [27], imaging [28, 29], secure communications [30, 31], and so on. Their utilities in practical settings, however, depend critically on steering and propagating information-carrying photons reliably through working media, which can be scattering, lossy, and reflective. For example, atmospheric turbulence has been shown to pose a significant challenge for quantum communications in free space [32, 33].

One question of interest is then: can the advantageous features of classical Airy beams be replicated in quantum photon signals for novel quantum technologies of practical significance? Distinctly, while Airy beams are a manifestation of electromagnetic wave interference, their quantum counterpart in single photons must be interpreted as the modulation of the photons’ wavefunctions. To answer this question,
here we demonstrate quantum correlated photon pairs in finite-energy Airy modes using spontaneous parametric down conversion (SPDC) and subsequential spatial light modulation using a cubic phase mask followed by a Fourier lens. Through time-correlated photon counting, we verify the Airy spatial wavefunctions of the photons and their propagation along a parabolic trajectory. Importantly, we find that the spatial modulation on the photons does not introduce any observable degradation of quantum correlation between them. These Airy photons could be deployed in various quantum applications for remote sensing, imaging, communications, etc., thus creating new capabilities [34–41].

2. Experimental method

Figure 1 outlines our experimental setup. A continuous-wave (CW) laser (LaserBlade, Coherent Solutions) generates light at 1559.67 nm with \( \lesssim 100 \text{kHz} \) linewidth. The light passes through an electro-optic modulator to create a pulse train with
100 ps full width at half maximum (FWHM) and 10 MHz repetition rate, synchronized with a radio-frequency source that gates single photon detectors for measurement. The optical pulses are then amplified in an Erbium-doped fibre amplifier to obtain high peak power (~1 W), and guided through a fibre collimator, a half-waveplate, and a quarter-waveplate, before coupled into a magnesium-doped periodically poled lithium niobate (PPLN) waveguide through an aspheric lens. The PPLN, about 1 cm long, is temperature stabilized and phase matched to create SPDC pump pulses at 779.83 nm via second harmonic generation. The output pulses are then filtered with three short-pass filters which provide a total >180 dB extinction to remove any residual fundamental light. A 90:10 beamsplitter is used to tap 10% power of the second harmonic light for real-time monitoring and the remaining power is guided through an aspheric lens into the second PPLN waveguide with similar phase matching characteristics for photon-pair generation via SPDC (779.83 nm → 1554.7 nm + 1564.7 nm) [42–46]. The created photon pairs are coupled out and collimated by another aspheric lens before passing through a long pass filter with extinction of 50 dB to remove the 779.83 nm light pump pulses. After coupling into a fibre, the signal and idler photon pairs are picked at 1554.7 nm and 1564.7 nm respectively, using wavelength division multiplexers. The idler photons are guided through an optical fibre delay line and detected using an InGaAs avalanche photodiode (InGaAs APD) (ID210, ID Quantique) with 10% quantum efficiency and < 100 dark counts per second. The signal photons are guided through a fibre collimator to the Airy-beam setup shown in figure 1, before being detected using a second InGaAs APD. Each detected photon produces a TTL pulse which goes into a multi-channel time-to-digital converter (SENLS, HRM-TDC) for coincidence measurement.

The Airy-beam setup follows the standard approach of first producing a cubic phase modulation on a Gaussian incident beam using a 1.5 cm × 1.1 cm spatial light modulator (SLM) (Santec SLM-100), and then passing it through a Fourier transform lens [7, 8]. Here, two-dimensional Airy spatial modes are created for both classical light and the signal photons, whose transverse mode is given by

\[
E(x, y) = Ai\left(\frac{x}{x_0}\right)Ai\left(\frac{y}{y_0}\right)\exp\left[i\left(\frac{x}{x_0} + \frac{y}{y_0}\right)\right]
\]

where \(Ai\) stands for the Airy function, \(x_0\) and \(y_0\) are the scaling factors in \(x\) and \(y\) transverse directions, respectively, and \(\alpha\) is a truncation factor [18]. In this experiment, \(\alpha = 0.0217, x_0 = y_0 = 271 \mu m\) which corresponds to an Airy spatial mode with a main lobe \(\sim 434 \mu m\) FWHM. The phase mask is created numerically by discretizing the cubic phase over an 1.04 cm × 1.04 cm area (smaller than the SLM screen) with pixel size \(\sim 10.4 \mu m\). A linear phase modulation along the \(x\) direction is superposed on the cubic phase mask to deflect the modulated light into its first diffraction order [47] thus separating it from any unmodulated light that will be in the zeroth order. The total loss as the light go through the free-space setup is 22 dB. The spatial profile of the resulting two-dimensional Airy beam is directly measured using a NIR-IR camera (FIND-R-SCOPE Model No. 85700) with pixel resolution of 17.6 \(\mu m\).

Once the Airy-beam setup is verified and optimized using a CW laser at 1568.7 nm, the signal photons are switched in the same fibre and free-space optical paths. At the focal point of the Fourier lens, they are spatially modulated to be in a two-dimensional Airy wavefunction. From there, those Airy photons propagate for 3 meters along a parabolic, self-accelerating trajectory. Both the Airy wavefunction and parabolic trajectory are verified using quantum correlation measurement with the idler photon, by first collecting the Airy photons in a fibre and detecting them using an InGaAs APD.

3. Results and discussion

We first compare the quantum correlation between the signal and idler photons with and without the Airy modulation, by measuring the coincidence-to-accidental ratio (CAR) of the photon pairs in each case. The CAR is a standard characterization of second-order quantum coherence, defined as the ratio between coincident counts of signal and idler photons produced by the same SPDC pump pulses and those by different pulses. Detailed experimental procedures can be found in [46, 48]. In this experiment, the photon counts are recorded over 60 minutes and the pump peak power is 33 mW. For the measurement without modulation, the signal photons bypass the Airy-beam setup and propagate instead through an optical fibre of equivalent path length. For the measurement with modulation, the signal photons are guided through the Airy-beam setup and collected by a single-mode fibre (SMF-28) at the focal point of the Fourier lens using a fibre collimator consisting of an aspheric lens (Thorlabs C220TMD-C). The lens is chosen to have a clear aperture that is much larger than the main lobe of the Airy beam and a numerical aperture that matches the fibre for the maximum coupling efficiency. The measurement results are shown in figure 2, where the coincident counts for the unmodulated and Airy signal photons...
The result is plotted as green dots in scanning point the coincident counts are recorded with pump detection with the idler photons. In this measurement, at each time window and those in the accidental window, each about between the total coincidence counts within the coincidence are compared. The CAR values are calculated as the ratio to the fluctuations in each’s CCD images. The blue line is a linear fit to the Gaussian beam’s trajectory and green dots are the simulated trajectory with the green line as the best fit. Also shown is the block’s position. Lastly, we verify the accelerating propagation of the Airy photons. To this end, we first construct a classical Airy beam from a CW laser at 1568.7 nm as in figure 1, and examine its ability to go around an obstacle. As a reference, a collimated Gaussian beam (from TLS in figure 1) is introduced to overlap with the Airy beam’s path right at the focal point of the Fourier lens and after propagating 3 m, where the two are coupled into the same fibre coupler. To measure the beams’ trajectory, the phase mask for the Airy beam is rotated by 45 degrees so that the acceleration occurs along the perpendicular direction with respect to optical table. Figure 4 (a) shows the trajectories of the two beams using the NIR-IR camera, extracted from the images taken along the optical path at a constant height, along with the simulated position of the Airy beam’s main lobe using the exact phase mask for the SLM. The good agreement between the simulation and measurement validates our entire setup. To further examine the parabolic trajectory, a 1-cm wide block is inserted into the path of Gaussian beam by 1.2 mm in the middle between the iris and fibre collimator. The block impedes the Gaussian beam, causing its power collected in the fibre to drop by 90%. In contrast, it allows the Airy beam to travel around due to the parabolic propagation, causing only a 30% drop.

Then we swap in the Airy photons to test their parabolic propagation. Figure 4 (b) shows a typical histogram of the coincident counts between the Airy and idler photons, comparing the cases with and without the block. In this measurement, the pump pulse peak power is 33 mW and the integration time is 60 minutes. As shown, the coincidence counts for the two cases exhibit similar profiles (with shot-noise fluctuations in each time bin), but with the total coincident counts dropping by 28% when the blocked is inserted, which agrees with the results for the Airy beam. The CAR values without and with the block are 70 ± 3 and 62 ± 4, respectively. This highlights the potential of steering Airy photons on a controlled trajectory, which can be reconfigured in real time by using a computer programmed SLM without any moving optics. This feature could be exploited for

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**Figure 4.** (a) Peak-intensity trajectories of the Gaussian beam (blue dots) and Airy beam (orange dots), where the error bars correspond to the fluctuations in each’s CCD images. The blue line is a linear fit to the Gaussian beam’s trajectory and green dots are the the simulated trajectory with the green line as the best fit. Also shown is the block’s position. (b) Histogram of the coincident counting between the idler and Airy signal photons with and without the block.
robust free-space quantum communications beyond line-of-sight [51].

4. Conclusion

In conclusion, we have created quantum correlated photons in a Airy-shape wavefunction and verified their parabolic propagation trajectory. Through two-photon coincidence measurement, we have found that spatial modulation on the photons does not introduce any observable degradation to the quantum states of the correlated photon pairs. Our results suggest the feasibility of using structured photons with exotic spatial and temporal modes [52, 53] for practical advantages in long distance quantum communication [34, 35], quantum imaging [36–39], quantum key distribution [40], light-sensitive biological applications [41], and so on. Beside the Airy modes, there exists a multitude of spatiotemporal modulations [17, 54–57] that can be similarly applied to quantum photonic signals to attain distinct advantages for various applications. A necessary condition for these exotic quantum beams is that quantum coherence is maintained over their transverse modes. For Airy photons in particular, it will be interesting to study how the truncation factor in equation (1) could affect the quantum correlation; that is, to what spatial extent the modulation does not significantly degrade the quantum state of the photons. Finally, the present experiment applies phase modulation directly on the generated photons, which induces loss and significantly reduces the photon production rate. This problem can be solved by using the lossless photon shaping technique [49].

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