High-visibility nonclassical interference of photon pairs generated in a multimode nonlinear waveguide

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Abstract: We report measurements of two-photon interference using a cw-pumped type-II spontaneous parametric down-conversion source based on a multimode periodically poled potassium titanyl phosphate waveguide. We have used the recently demonstrated technique of controlling the spatial characteristics of the down-conversion process via intermodal dispersion to generate photon pairs in fundamental transverse modes, thus ensuring their spatial indistinguishability. Good spatial overlap of photon modes within pairs has been verified using the Hong-Ou-Mandel interferometer and the preparation of polarization entanglement in the Shih-Allee configuration, yielding visibilities consistently above 90%.

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1. Introduction

Multiphoton interference is a nonclassical effect widely utilized in optical realizations of quantum-enhanced technologies [11] and testing foundations of quantum mechanics. High visibility of multiphoton interference depends critically on the absence of distinguishing information between the interfering photons [2]. While early experiments relied on spatial and spectral filtering to fulfill this requirement, a great deal of effort is currently being expended on the development of sources that guarantee suitable characteristics of the collected photons already at the production stage. Such sources can offer substantially higher brightness, compatibility with integrated optics circuits, and strong photon number correlations, the last feature needed for example in device-independent quantum cryptography and randomness generation [3, 4].

A promising route to photon sources with well-defined, controllable characteristics is based on spontaneous parametric down-conversion in $\chi^{(2)}$ nonlinear waveguides [5, 6, 7, 8, 9]. Compared to bulk crystals, the phase matching conditions that define the nonlinear process in a waveguide assume a different form owing to the discreteness of transverse spatial modes propagating through the structure. This opens up new possibilities to engineer properties of the produced nonclassical radiation [10]. In particular, generation of spatially pure photon pairs in a multimode waveguide has been recently reported in Ref. [11], with a high degree of spatial coherence verified via a heralded photon counting measurement of the beam quality factors based on free-space diffraction. Single spatial modes for the generated photons were selected by exploiting the effects of intermodal dispersion in the down-conversion process. This technique overcomes waveguide manufacturing limitations for shorter wavelengths. It can also be prospectively used to produce spatial photonic entanglement [12, 13].

In this paper, we study experimentally two-photon interference using a periodically poled potassium titanyl phosphate (PPKTP) waveguide source of spatially pure photon pairs that relies on the technique of exploiting intermodal dispersion. Measurements performed in two setups: a Hong-Ou-Mandel interferometer [14] in the common-path configuration and a Shih-Alley source of polarization entanglement [15] yield visibilities consistently exceeding 90%. Remarkably, these values have been obtained without any spatial filtering of the generated photons, and only a coarse selection of their spectral range. These results provide a compelling verification of the high-quality modal characteristics of the generated photons, paving way towards employing them in more complex multiphoton interference experiments.

2. Experimental setup

The waveguide source of photon pairs used in our experiments is shown schematically in Fig. [1]. Its heart was a 1 mm long PPKTP structure (AdvR Inc.) temperature stabilized at $19.0 \pm 0.1 ^\circ C$ using a thermoelastic cooler. A series of waveguides localized just beneath the surface had lateral transverse dimensions of approx. 2 $\mu$m, effective depths of approx. 5 $\mu$m, and poling...
periods designed for efficient type-II second harmonic generation in the 800 nm wavelength region. At these wavelengths the waveguides supported at least 8 transverse spatial modes (4 for each polarization). The structure was placed between two 50 x microscopic objectives with numerical apertures NA = 0.55 for incoupling and NA = 0.8 for outcoupling.

The down-conversion process was pumped by a narrowband (linewidth < 0.0011 nm) cw diode laser (Toptica BlueTune) that could be tuned around the central wavelength of 400 nm. Pump power and polarization were controlled using a Glan-Taylor polarizer placed between two half-wave plates. Typical pump power was of the order of 20 µW, measured after the outcoupling objective. As preparing the pump in the fundamental transverse waveguide mode was crucial for the spatial purity of the generated photons \[11\], after the outcoupling objective the remainder of the pump beam was directed with a dichroic mirror to a CCD camera to monitor the pump spatial mode in the waveguide. An auxiliary infrared beam from a modelocked Ti:sapphire laser, coupled into the fundamental spatial mode of the waveguide at the down-converted wavelength, was used to identify the waveguide with a suitable poling period and to align optical elements following the source.

In order to verify the spectral indistinguishability of the generated photon pairs, in the first step we measured individual spectra of heralded photons using the setup depicted in Fig. 1(a). Photon pairs were sent through a color filter (cut-off wavelength 660 nm) and separated on a polarizing beam splitter. The output paths for the photons could be swapped with the help of a half wave plate located before the polarizing beam splitter. At the output, one photon was used as a herald, while the second one was transmitted through a 0.7 nm FWHM interference filter mounted on a motorized rotation stage. The photons were subsequently coupled using 11 mm focal length aspheric lenses into 100 µm core diameter, 0.22 NA multimode fibers connected to single photon counting modules (Perkin Elmer SPCM-AQRH-14-FC). Coincidence events were counted within a 3 ns window. The rotation angle of the interference filter was calibrated in terms of the transmitted central wavelength using a Ti:sapphire beam and a spectrometer.

PPKTP phase matching properties make the spectral characteristics of photons strongly de-
dependent on the pump wavelength. Using the overlap of the single photon spectra as the optimization criterion, we fine-tuned the wavelength of the pump laser, obtaining the best match at 400.63 nm, shown in Fig. 2. In the same graph, we also depict power transmission profiles of two interference filters used in measurements of two-photon interference described in Sec. 3. The filters have FWHM widths approximately 11 nm and 3 nm. The broader filter encompasses the entire spectra of photons generated in fundamental spatial modes. Its principal role in the setup is to cut off down-conversion processes involving higher spatial modes that occur in distinct frequency regions [11, 13].

3. Two-photon interference

We have tested nonclassical interference between photons generated in the waveguide using two setups. The first one was the Hong-Ou-Mandel interferometer [14] in the common-path configuration [15] as depicted in Fig. 1(b). In this case, a pair of orthogonally polarized photons was rotated by 45° with a half-waveplate and sent to a polarizing beam splitter. The time delay between the photons was adjusted using a Babinet-Soleil compensator. Zero delay was found by measuring spectral fringes using the Ti:sapphire beam. Photons leaving the polarizing beam splitter were coupled into multimode fibers and counted using the same configuration as before.

In Fig. 3 we show measured coincidence rates as functions of the time delay. The depth of the Hong-Ou-Mandel dip with respect to the reference level of fully distinguishable particles, determined from gaussian fits, is $\gamma = 91.1 \pm 0.5\%$ for 11 nm filter and $\gamma = 93.1 \pm 1.2\%$ for 3 nm filter. These figures confirm that the photons are highly indistinguishable in both the spectral and the spatial degrees of freedom. It is seen that the coincidence count rate is minimized for a non-zero delay of $-0.08$ ps, which compensates the temporal walk-off within photon pairs due to waveguide birefringence.

The second test of two-photon interference was carried out through preparation of polarization entanglement in the Shih-Alley configuration [16]. In this setup, shown in Fig. 1(d), two photons in orthogonal horizontal (H) and vertical (V) polarizations impinge on a non-polarizing beam splitter at a nearly normal incidence. Their polarizations are analyzed at the
outputs using half-wave plates and polarizers. When the two photons emerge at different ports of the beam splitter, their postselected polarization state takes the maximally entangled form \((|HV\rangle + |VH\rangle)/\sqrt{2}\). The presence of entanglement can be verified by detecting photons in linear polarization bases. Specifically, if one of the photons is detected at \(45^\circ\), the coincidence rate with the second detector measuring photons at an angle \(\theta\) is proportional to

\[
R(\theta) \propto \frac{1}{4}(1 + \gamma \sin 2\theta),
\]

(1)

where the real parameter \(\gamma\) characterizes fringe visibility. It can be shown [17] that for temporally compensated photons this parameter is theoretically equal to the depth of the Hong-Ou-Mandel dip, hence the use of the same symbol for both quantities.

Before measuring polarization fringes, the Babinet-Soleil compensator placed before the non-polarizing beam splitter was set to the position that minimized the coincidence rate in the Hong-Ou-Mandel interferometer. In Fig. 4 we present coincidence count rates between one
 photon projected onto horizontal (H), vertical (V), diagonal (D), or antidiagonal (A) polarization and the second photon detected in linear polarization at an angle \( \theta \). Visibilities determined from sinusoidal fits to interference fringes are collected in Tab. Fringe visibilities for diagonal and antidiagonal polarizations match within their uncertainties the depths of Hong-Ou-Mandel dips.

Table 1. Visibilities of polarization fringes obtained from measurements for multimode (MMF) and single mode (SMF) fibers in the setup for polarization entanglement preparation. Absolute uncertainties of presented values are approximately 1%.

| Coupling fiber | Interference filter | Fringe visibility |
|---------------|---------------------|-------------------|
|               | H                   | V                 | D      | A      |
| MMF           | 11 nm               | 93.9%             | 94.0%  | 92.8%  | 90.9%  |
|               | 3 nm                | 94.4%             | 96.2%  | 93.0%  | 93.3%  |
| SMF           | 11 nm               | 96.3%             | 96.8%  | 95.7%  | 95.9%  |
|               | 3 nm                | 98.1%             | 97.4%  | 97.9%  | 98.6%  |

In order to estimate the effects of nonideal spatial overlap of the interfering photons, we repeated the measurements of polarization correlations using single mode fibers to deliver photons to detectors. Fringe visibilities determined from these data are also presented in Tab. It is seen that for measurements in the diagonal basis, fringe visibilities increased by approximately 5%. This can be mainly attributed to transverse walk-off of orthogonally polarized photons in the Babinet-Soleil compensator, a minor discrepancy between fundamental waveguide mode profiles for orthogonal polarizations, and contributions from down-conversion processes involving residually excited higher-order pump modes.

Typical ratio of coincidence to single count rates in our experiments was 8.9% for the 11 nm filter. Although standard optical elements were antireflection-coated, contributions to non-unit transmission come from the waveguide-air interface (\( \approx 92\% \)), outcoupling objective (\( \approx 76\% \)), Soleil-Babinet compensator (\( \approx 75\% \)), interference filter (\( \approx 77\% \)), coupling into multimode fibers (\( \approx 85\% \)) and are further combined with the non-unit detector efficiency (\( \approx 45\% \)). Other relevant effects may include intra-waveguide losses and additional down-conversion processes involving nonguided modes in the bulk medium surrounding the waveguide.

4. Conclusions

We studied experimentally distinguishability of photons generated via spontaneous parametric down-conversion in a multimode nonlinear PPKTP waveguide. Measurements taken in two different setups implementing two-photon interference yielded visibilities robustly above 90% without resorting to spatial filtering. This directly demonstrates that photon sources based on exploiting intermodal dispersion in multimode structures, a key technique used in our setup, are suitable for multiphoton interference experiments. The benefits of waveguide sources in photonic quantum technologies, such as high brightness and integrability, can be therefore extended also to spectral regions where single-mode structures are not readily available.

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