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Spectral correlation and interference in continuous-wave non-degenerate photon pairs at telecom wavelengths

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Abstract

We have developed an entangled photon pair source based on a domain-engineered, type-II periodically poled lithium niobate crystal that produces signal and idler photons at 1533 nm and 1567 nm. We characterized the spectral correlations of the generated entangled photons using fiber-assisted signal-photon spectroscopy. We observed interference between the two down-conversion paths after erasing polarization distinguishability of the down-converted photons. The observed interference signature is closely related to the spectral correlations between photons in a Hong- Ou-Mandel interferometer. These measurements suggest good indistinguishability between the two downconversion paths, which is required for high entanglement visibility.

Keywords

quantum optics; interference; polarization entangled pair source; spontaneous parametric downconversion; entanglement

1. INTRODUCTION

Entangled photon pairs are important for quantum information systems. Photon pairs generated by spontaneous parametric down-conversion (SPDC)^{1,2} are an important tool for distributing entanglement between different systems and across large distances. These pairs have been used in many quantum information applications including quantum key distribution³, connecting quantum nodes⁴, tests of Bell's inequality⁵⁻⁸, and generation of certified random numbers⁹. Indistinguishability of certain degrees of freedom of the entangled photons is a key requirement for high-quality entanglement since distinguishing information (such as wavelength, arrival time, or direction of travel) can destroy the interference effects that are a fundamental part of entanglement experiments^{10,11}. However, it is possible to design an entangled-photon-pair source with unequal or non-degenerate signal and idler wavelengths. In these sources, interference occurs between photons

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generated in two down-conversion paths, such as two paths in an interferometer^{12–14}, or two separate nonlinear crystals^{15,16}.

A common method for measuring photon distinguishability is to use a Hong-Ou-Mandel (HOM) interferometer¹⁷. Recently, spectrally resolved studies of HOM interference have been performed¹⁸, which give additional insights into the origins of the indistinguishability. The spectral dependence of correlations is obtained using fiber-assisted single-photon spectroscopy^{18–21}. This spectroscopy technique is fast and powerful. It translates the fine temporal resolution of photodetectors such as superconducting nanowire single-photon detectors (SNSPDs) into fine spectral resolution by sending the spectrum under test through a dispersive delay line, typically a long section of optical fiber. Single-photon-level spectra can be acquired quickly using time-correlated single-photon-counting electronics. Post-processing allows observation of spectrally-resolved photon correlations.

We apply fiber-assisted single-photon spectroscopy to a photon-pair source based on spontaneous parametric down-conversion using a continuous-wave (CW) pump laser. This source is designed to produce signal (*s*) and idler (*i*) photons at 1533 nm and 1567 nm, respectively. We used periodically poled LiNbO₃ (PPLN) with an aperiodic domain structure^{22–24} that is designed to simultaneously phasematch $|H_s V_i\rangle$ and $|V_s H_i\rangle$ ^{25,26}, where H and V represent horizontally and vertically polarized photons, respectively. The crystal with the aperiodic domain structure generates the photon pairs in a distributed fashion, which may have advantages over schemes that use two separate co-rotated crystals^{27,28} or two consecutive quasi-phasematching periods^{29,30}. The observed single-photon spectra agree well with theoretical calculations. We explore the distinguishability of the two parallel down-conversion processes through these measurements. We observe an interference feature that we identify as interference between the two possible down-conversion paths.

2. FIBER-ASSISTED SINGLE-PHOTON SPECTROSCOPY

Superconducting nanowire single photon detectors have remarkably high detection efficiency (up to 93% efficiency) and very small timing jitter (<100ps)³¹. This fine temporal resolution can be translated to spectral resolution by incorporating a dispersive medium so that different wavelength components of the test light arrive at the detector at different times. This is the underlying principle of fiber-assisted, single-photon spectroscopy^{18–21}, where the dispersion is provided by a long length of optical fiber or a more compact fiber dispersion compensation module (DCM).

We first characterized the dispersion produced by the DCM. Figure 1a shows the measured relative time delay of different spectral components passing through the DCM. The slope of this data with respect to wavelength gives the dispersion, which is shown in Fig. 1b. At 1550 nm wavelength, the DCM produces –1.0 ns/nm dispersion. The negative sign of the dispersion indicates that longer wavelengths lead the shorter wavelengths.

Figure 2 shows the experimental setup. The 25-mm long, domain-engineered PPLN crystal is pumped with a continuous-wave 775-nm wavelength laser that has linewidth below 200 kHz. The pump is focused confocally to a 40μm waist inside the crystal. After the PPLN, the

pump is filtered out with a dichroic mirror and the orthogonally polarized signal and idler photons are sent to a half-wave plate (HWP) and polarization beam splitter (PBS). For most measurements, the HWP is removed altogether or positioned to have no effect so that the horizontally polarized photons are transmitted and the vertically polarized photons are reflected by the PBS. For certain measurements, the HWP is positioned to produce 45° of polarization rotation, which effectively makes the PBS a non-polarizing beam splitter. After the beam splitter, both beams are coupled into optical fibers. We did not fully optimize the collection efficiency, which was around 5–10%. We incorporated a DCM into one of the arms after the beam splitter. With a single DCM, the undispersed arm after the PBS serves as a trigger while the other arm is dispersed by roughly 1 ns/nm. The DCM has 4 dB insertion loss and produces 30 μ s of fixed delay. The photons were detected by SNSPDs and the arrival times analyzed with time-tagging electronics.

In contrast to pulsed SPDC sources that use the pump pulses as a trigger for the timing electronics in fiber-assisted single-photon spectroscopy, we use the fact that the pump is narrowband, which means there is a one-to-one correspondence in wavelength between the down-converted signal and its matching idler photon. Therefore, the relative arrival time between the signal and idler photons uniquely determines the wavelengths of both photons. Using a calibration of the DCM delay as a function of wavelength, we constructed a look-up table between signal-idler arrival time and wavelength. This mapping is shown in Fig. 3. The x -axis in the figure is given in relative delay, with t set to 0 at 1550 nm wavelength. We calibrate the delay caused by experimental path imbalances by examining data where the HWP and PBS together act as a non-polarizing beam splitter and look for symmetry when the measured data are reflected above $2\lambda_{\text{pump}}$.

3. EXPERIMENTAL RESULTS

Figure 4 shows SPDC spectra at different temperatures measured with the fiber-assisted spectroscopy technique. The HWP is not used in these spectrograms. The x -axis is the wavelength associated with the dispersed photons that arrive at D1, in this case, the horizontally polarized photons. The wavelengths of the corresponding vertically polarized photons can be calculated using energy conservation. The H photons tune to longer wavelengths with increasing temperature, while the V photons tune to shorter wavelengths. At $T=143^\circ\text{C}$, the wavelengths of the H and V polarized photons become equal, $\lambda(H_s) = \lambda(V_s)$ and $\lambda(H_i) = \lambda(V_i)$. These spectra agree with previously measured spectra based on difference frequency generation^{25,26}.

The half-wave plate has several interesting effects on the experiment. When the HWP is set to rotate all polarizations by 45° , it removes the polarization selectivity of the polarizing beam splitter. For the fiber-assisted spectrogram measurement, the effect of the HWP is to send both H- and V-polarized photons to both arms. This causes both H-polarized and V-polarized photon peaks to register in the spectrogram, as illustrated in Fig. 5. Observation of the four peaks allows the fixed time delay between the two arms to be detected with high accuracy. This time delay is the reference delay that, when combined with the wavelength calibration, allows proper matching of both pairs of H- and V-polarized peaks. As a result, a careful characterization of the fixed delay difference between the two arms is not necessary.

When the HWP erases polarization distinguishability of the PBS, the spectrograms reveal an interference signature that is related to interference between the two down-conversion paths (see Fig. 6a). With the HWP present and the PPLN temperature at 138 °C where $\lambda(H_i)$ $\lambda(V_i)$, two separate peaks are visible in the spectrogram near 1565 nm (pale gray trace). When the crystal temperature is raised to 143 °C, the wavelengths of the two peaks overlap and we see interference (gray trace). However, when the HWP is removed, the interference disappears (black trace). There is a clear difference in the shape of the spectrograms caused by the presence or absence of the HWP.

4. DISCUSSION

The interference seen in Fig. 6a is due to interference of the two down-conversion paths. The HWP plays a critical role in making the two down-conversion paths indistinguishable. The sketch in Fig. 7 illustrates the role of the HWP for interference. Without the HWP rotating the polarizations by 45° the two down-conversion paths ($|H_s V_i\rangle$ or $|V_s H_i\rangle$) are distinguishable after separation by the PBS. The paths are distinguishable in the sense that the wavelength of the photon arriving at one detector immediately reveals which path was taken. When the HWP rotates the polarizations and removes the polarization distinguishability of the PBS, this distinguishability is erased and interference becomes possible. The HWP enables the interference between the two down-conversion paths.

The interference fringes can be understood in terms of spectrally resolved HOM interference. The joint spectral intensity (JSI) distribution of two photons exiting opposite ports of a beam splitter is given by^{18,32}

$$I(\omega_1, \omega_2) \propto \frac{1}{2} \left| C(\omega_1, \omega_2) e^{i(\omega_1 t_1 + \omega_2 t_2)} - C(\omega_2, \omega_1) e^{i(\omega_2 t_1 + \omega_1 t_2)} \right|^2, \quad (1)$$

where $C(\omega_1, \omega_2)$ is the joint spectral amplitude of the two-photon wavefunction incident on the beam splitter, ω_1 and ω_2 refer to the frequencies of the two photons, and t_1 and t_2 are their corresponding arrival times. When $t = t_1 - t_2 = 0$, the HOM interference dip is obtained if

$$C(\omega_1, \omega_2) = C(\omega_2, \omega_1). \quad (2)$$

If the SPDC is degenerate, then Eq. (2) is satisfied since $\omega_1 = \omega_2$. However non-degenerate SPDC sources can show HOM interference if the joint spectral amplitude is engineered to satisfy Eq. (2). This requirement is identical to the stipulation that the joint spectral amplitude $C(\omega_1, \omega_2)$ be symmetric about the line $\omega_1 = \omega_2$ when plotted in the $\omega_1 - \omega_2$ plane³². Our SPDC source achieves this symmetry at a crystal temperature of 143 °C. Figure 8a shows the joint spectral intensity distribution of the source, $|C(\omega_1, \omega_2)|^2$, for the process near (1532 nm, 1568 nm). This distribution is the narrowband pump multiplied by the sinc^2 phasematching function. The nonlinear crystal is approximated by two QPM periods that phasematch $|H_s V_i\rangle$ and $|V_s H_i\rangle$. The CW pump laser is modeled as having 0.3 pm bandwidth.

Eq. (1) shows that interference fringes are present all along the HOM interference dip¹⁸. That is, if one calculates $I(\omega_1, \omega_2)$ for different t , oscillations are present in the JSI

distribution for $t = 0$. The spectral fringes increase in frequency with larger t . In our experiment, the signal and idler arrive at the beamsplitter at unequal times because of temporal walkoff due to birefringence in the PPLN crystal. For LiNbO₃, the index difference at 1550 nm is $n = 0.0732$ ³³, so that $t = nL / 2c = 3$ ps. As a comparison, the width of the HOM dip is given by the coherence time of the photon packet¹⁷. From spectral measurements, the bandwidth of the downconversion is $\Delta f = 4.2$ cm⁻¹ for $\lambda = 1$ nm so that the coherence time³⁴ is $\sqrt{2\ln 2/\pi}/\Delta f = 5.3$ ps. Thus the measurements taken here occur on the shoulder of the HOM dip.

We can use Eq. (1) together with LiNbO₃ dispersion data³³ to calculate the expected joint spectral intensity distribution for HOM interference. Figure 8b shows the calculated spectral correlations near the HOM dip with $t = 3$ ps. Projecting this theoretical distribution on the vertical axis give the calculated spectrum shown in Fig. 6b, which is in good agreement with the experimental interference spectrum. Note that the resolution of our spectrometer (0.1 nm) limits the visibility of the experimental fringe. There is also a slight offset between the center wavelength of the calculated and measured spectra, which is likely due to uncertainty in the dispersion function.

Photon-pair sources with unequal signal and idler wavelengths show interference, and this interference can only be understood by considering the total biphoton wavepacket. It is clear from the sketch in Fig. 7 that the interference is not between individual photons but between the different paths. Each of the two paths contain pairs of photons with non-degenerate wavelengths. The wavelengths of the photons in one path must match the wavelengths in the other path, otherwise there is distinguishing information and there is no interference (see the pale gray trace in Fig. 6a, for instance). It is this path interference that allows entanglement using non-degenerate signal and idler wavelengths.

We believe that this measurement is a useful part of a full characterization of the polarization-entangled photon pair source. The clear interference signature suggests that the source has good indistinguishability between the two simultaneous down-conversion processes. The next step will be to measure the polarization correlations⁵. The interference fringes observed through spectrally resolved HOM interference suggest that once temporal distinguishability is removed by temporal compensation, the source will have good polarization entanglement performance. In fact, the spectrally resolved HOM measurement could be a useful tool towards diagnosing sources of distinguishability that lead to poor polarization correlations.

5. CONCLUSION

In conclusion, we have developed a dual-process SPDC crystal based on PPLN and we characterized the parametric down-conversion using fiber-assisted single-photon spectroscopy. We have used this technique to perform spectrally resolved HOM interference. We observed interference between the two down-conversion paths and show how this interference depends on erasing the polarization distinguishability. A theoretical model for the interference is presented, which shows excellent agreement with the experimental spectrogram. Observation of the interference is complementary to the measurement of

polarization correlation, and it is a useful stepping stone towards demonstrating the utility of this source for entangled photon pair generation.

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Figure 1.

(a) Relative time delay of different wavelengths passing through the dispersion compensation module. (b) Dispersion produced by the DCM. At 1550 nm, the dispersion is -1 ns/nm.

Figure 2.

Sketch of experimental setup. The PPLN crystal is pumped by a CW 775 nm laser. Horizontally and vertically polarized photons near 1550 nm are produced by SPDC. The down-converted photons are incident on a beam splitter (polarizing beam splitter when the HWP is removed, and non-polarized beam splitter when the half-wave plate (HWP) rotates polarizations by 45°) and then coupled into optical fibers. The light is dispersed with dispersion compensation module DCM then detected by SNSPDs (D1 and D2). Arrival times are logged using time-tagging electronics.

Figure 3.

Map of difference in arrival times of photons at D1 and D2 (Δt) to the wavelength of one of the photons for DCM in only one arm of the experiment. We set $\Delta t = 0$ for 1550 nm, which is $2\lambda_{\text{pump}}$, where the signal and idler wavelengths would be degenerate.

Figure 4. Temperature tuning of the domain-engineered PPLN crystal. Each trace is measured with no HWP and integration time of one minute.

Figure 5. SPDC spectra measured with and without the half-wave plate. Inserting the HWP to erase polarization selectivity of the PBS causes both H- and V-polarized peaks to appear in spectrogram.

Figure 6.

(a) Temperature tuning to $T=143\text{ }^{\circ}\text{C}$ (where wavelengths are equal) reveals interference in the spectrogram. Interference disappears when the HWP is removed. (b) Comparison of theoretical interference spectrogram (dashed) to experiment (solid). The small offset in the center wavelength can be attributed to uncertainty in the dispersion relation.

Figure 7.

(a) Without the HWP, the paths are distinguishable since the wavelengths of signal and idler are different. (b) With the HWP (which causes H- and V-polarizations to be sent to both arms), the paths are indistinguishable.

Figure 8.

Theoretical (a) joint spectral distribution of the source, $|C(\omega_1, \omega_2)|^2$, and (b) joint spectral intensity distribution after HOM interference calculated from Eq. (1) using $t = 3$ ps. The plots show the joint spectrum of the process near (1532 nm, 1568 nm) while the other process (not shown) is at (1568 nm, 1532 nm). There is slight asymmetry in the JSI after interference compared to $|C(\omega_1, \omega_2)|^2$ shown in (a).