Observation of spectral asymmetry in cw-pumped type-II spontaneous parametric down-conversion

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We report on a spectral asymmetry in cw-pumped type-II spontaneous parametric down-conversion. We observe that when the pump beam is focused, the spectra of ordinary and extraordinary down-converted photons broaden unequally. Theoretical analysis indicates that this asymmetry can be attributed to the difference in the angular dispersion (walk-off) of the two kinds of photons, coupled with the well-known correlation between wavelength and emission direction.

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Photonic entanglement is an important resource for a variety of applications, including fundamental studies of the foundations of quantum mechanics [1,2], quantum communication [3], and linear optical quantum computing [4]. The most common method for the generation of entangled photons is spontaneous parametric down-conversion (SPDC), in which a pump photon decays to two daughter photons. Due to conservation of energy and momentum, these photons are typically entangled in multiple degrees of freedom and certain source configurations lead to entanglement in the polarization degree of freedom. Whereas many applications make use of polarization entanglement, there is an increasing interest in the spectral and spatial properties of down-converted photons and, specifically, in achieving particular spatial and spectral profiles [5–9].

The spectral and spatial characteristics of SPDC photons are influenced both by the phase-matching properties of the medium and by the spectral and spatial composition of the pump light. Previous works have shown a number of interesting relationships. A broadband pump, for example, has been shown to lead to different signal and idler spectra in type-II SPDC [10]. Likewise, the signal and idler spatial modes are related to the spatial mode of the pump [11]. This relationship has been exploited to improve SPDC coupling to single-mode collection optics [12], although polarization-dependent differences have been observed [13,14]. Some spatial-spectral effects have also been observed. It was shown in [6,7] that focusing the pump in the case of type-I SPDC can lead to larger down-conversion bandwidths, thereby increasing the measurement precision in, for example, Hong-Ou-Mandel interferometry [15] or quantum optical coherence tomography [16,17].

In this paper we extend the line of such studies, particularly [6,7] to the case of type-II SPDC with a focused monochromatic pump. As in the type-I case, we find that the signal and idler spectra are broadened by the effects of pump focusing. But here we report the somewhat surprising observation that in the case of type-II SPDC, the effect can be much weaker for photons of one polarization, leading to ordinary and extraordinary photons with very different bandwidths. This spectral asymmetry between the two polarizations is surprising because, with a monochromatic pump, conservation of energy usually requires the signal and idler spectra to be mirror images of each other. We present a model that shows that the observed effect is related to a previously reported spatial asymmetry associated with a focused pump in type-II SPDC [13,14]. Because the spatial and spectral properties are coupled in SPDC emission, the spatial asymmetry leads to the spectral asymmetry reported here.

A schematic of the experimental apparatus is shown in Fig. 1. Photon pairs were generated in a 2-mm type-II beta-barium borate (BBO) nonlinear crystal pumped by a cw Ar+ laser at 351.1 nm. The crystal was oriented so as to generate pairs of polarization-entangled photons in a standard type-II SPDC configuration [18]. Using a dispersion compensation system, ultraviolet filters to block pump light, narrow-band spectral filters [full width at half maximum (FWHM) = 3 nm], and single-mode fiber-coupled single-photon detectors, the system was aligned to generate the maximally entangled polarization state \( \langle |H\rangle |V\rangle + |V\rangle |H\rangle \rangle / \sqrt{2} \). After this state was verified by an observation of >98% visibility in both the rectilinear and diagonal polarization bases, the compensation system and narrow-band filters were

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FIG. 1. (Color online) Schematic of the experimental apparatus. A cw Ar+ laser at 351.1 nm was focused into a 2-mm type-II beta-barium borate (BBO) crystal. Various lenses were used to obtain different focusing conditions. After passing through a pair of Michelson interferometers [consisting of beam splitters (BS), mirrors, and polarizers (Pol)], the down-converted photons were collected into single-mode fibers and detected by single-photon-counting detectors (d). By adjusting the delay in each interferometer, we were able to observe single-photon interference and determine the coherence length of photons in each path.
removed and the photons were directed into two Michelson interferometers (MIs) consisting of beam splitters, mirrors, and polarizers. The polarizers were included to select between ordinary or extraordinary polarizations. The outputs of the MIs were again focused into single-mode fibers and detected with single-photon-counting detectors. The two collection systems were placed about 55 cm from the BBO crystal. Single-photon interference fringes were observed by moving the MI mirrors on motorized translation stages in steps of 300 nm. The coherence length of down-converted photons could thus be measured from single-photon interference fringes. It should be noted that, after removing the dispersion compensation system, the ordinary and extraordinary photons were slightly displaced from one another due to transverse and longitudinal walk-off in the down-conversion crystal. Therefore, slight adjustments to the collection systems were required when switching between polarizations.

Single-photon interferograms were obtained for three different pump configurations: weakly focused, moderately focused, and strongly focused. In this regard, the experiment is similar to previous works involving a focused cw pump in type-II SPDC [13,14]. In those works, an asymmetric broadening of the far-field spatial distribution was observed when the pump was focused. However, attention was restricted to a small wavelength range. Here, under similar focusing conditions, the MIs are used to study the spectral broadening of photons collected over a small angular range.

The pump was initially weakly focused to give a beam waist \( w = 74 \, \mu m \) (measured using the knife-edge method) inside the BBO crystal. As the pump beam was close to the collimated condition, the ordinary and extraordinary photon densities are nearly equal where the two down-conversion cones overlap [13]. Consequently, the spectra for the two polarizations are expected to be identical. The normalized single-photon interferograms for ordinary and extraordinary photons in one arm of the setup are shown in Figs. 2(a) and 2(b). The envelopes of these interferograms have been fit with functions of the form \( 1 + \gamma \exp[-2(d/l)^2] \), where \( d \) is the mirror displacement, \( l \) is the coherence length, and \( \gamma \) is the visibility. The fits give a coherence length \( l = 46 \, \mu m \) for both polarizations, indicating spectral symmetry between the two polarizations. Measurements of photons in the other arm of the setup yield a similar result, with both ordinary and extraordinary photons having a coherence length of 46 \( \mu m \). The experimental results under these conditions are consistent with previous observations [19].

The situation is markedly different, however, when the pump is focused more strongly. The interferograms in Figs. 2(c) and 2(d) correspond to the ordinary and extraordinary photons for the case in which the pump is focused to a waist size \( w = 30 \, \mu m \), and for Figs. 2(e) and 2(f), the pump was focused to 20 \( \mu m \). The shorter coherence lengths show that both polarizations experience spectral broadening as the pump is focused. However, the effect is much more pronounced for the extraordinary photons—the coherence lengths for the moderate and strong focusing cases are 27 \( \mu m \) and 15 \( \mu m \), respectively, whereas the corresponding coherence lengths for the ordinary photons are 42 \( \mu m \) and 30 \( \mu m \), respectively.

![FIG. 2.](Color online) Observation of increasing spectral asymmetry between ordinary (o) and extraordinary (e) polarizations in cw-pumped type-II SPDC with a focused pump. Single-photon interference fringes (points and connecting lines) were observed in a Michelson interferometer and then fit to Gaussian envelopes (solid lines) to determine the coherence lengths. For the sake of clarity, the plots have been individually normalized to their respective mean count rates, which ranged from 30000/\( s \) to 80000/\( s \). Data were taken for three different focusing conditions of the pump beam. The pump beam waists are 74 \( \mu m \) in (a) and (b), 30 \( \mu m \) in (c) and (d), and 20 \( \mu m \) in (e) and (f). The coherence lengths obtained from the fit are 46 \( \mu m \), 46 \( \mu m \), 42 \( \mu m \), 27 \( \mu m \), 30 \( \mu m \), and 15 \( \mu m \) for (a), (b), (c), (d), (e), and (f), respectively.

A simple theoretical treatment reveals that the phenomenon of Fig. 2 is a consequence of the different spatial and spectral dispersion of the ordinary and extraordinary photons. To lowest order the longitudinal component of the wave vector of a field can be written as [20]

\[
k_l = \frac{n \omega}{c} + \alpha k_\perp + \frac{n'}{c} \Omega,
\]

where \( n \omega/c \) is the internal wave number, \( \alpha \) is the walk-off angle, \( k_\perp \) is the transverse component of the wave vector [related to the external angle by \( \sin \theta = k_\perp/(n \omega/c) \)], \( n' \) is the group index, and \( \Omega \) is the detuning relative to some nominal frequency. For simplicity, we consider only the transverse dimension in the plane of the walk-off and assume collinear propagation. For a monochromatic focused pump, conservation of energy and transverse momentum imposes the condi-
tions $\Omega_s+\Omega_i=0$ and $k_{\perp s}+k_{\perp i}=k_{\perp p}$, respectively. The phase mismatch $\Delta k = k_p - k_s - k_i$ reduces to just the longitudinal component, which is
\[
\Delta k = \frac{n_i^s - n_i^i}{c} \Omega_s + \frac{\alpha_s - \alpha_i}{\alpha_p - \alpha_i} k_{\perp s} + \frac{(\alpha_p - \alpha_i) k_{\perp i}}{\bar{L}^2},
\] (2)
under the assumption that the interaction is phase matched for the collinear process. (The subscript “p” denotes the pump field. We use “s” and “i” to denote signal and idler photons, as the derivation which follows is valid for both type-I and type-II down-conversion. In the present context, signal and idler are synonymous with ordinary and extraordinary photons, as the derivation which follows is valid for both type-I and type-II down-conversion.)

Noting that, for a given pair of signal and idler wavelengths, the expression above implies $k_{\perp s}/k_{\perp i} = -(\alpha_p - \alpha_i)/(\alpha_p - \alpha_i)$. That is, $k_{\perp}$ tends to be larger for the photon whose walk-off angle is more similar to that of the pump (which in our experiment is extraordinary). This results in an unequal spatial broadening of the ordinary and extraordinary emission cones as the pump is focused [15,14]. As we will now show, this spatial asymmetry leads to a corresponding asymmetry between the spectra of ordinary and extraordinary photons collected over a small angular range.

The two-photon amplitude is proportional to
\[
A(k_{\perp s},k_{\perp i},\Omega) \propto E_p(k_{\perp s} + k_{\perp i}) \sin \left(\Delta k \frac{L}{2}\right),
\] (3)
where $E_p(k_{\perp p})$ is the angular distribution of the pump. A focused Gaussian pump beam with angular width $\Delta \theta_p = \lambda_p/\pi w$ has an angular spectrum
\[
E_p(k_{\perp p}) \propto \exp[-(k_{\perp p} / K_p)^2],
\] (4)
where $K_p = (\omega/c) \sin \Delta \theta_p$. Using the approximation $\sin(x) \approx \exp(-\gamma x^2)$ for $\gamma = 0.193\ldots$, we write the two-photon amplitude as
\[
\frac{\Delta \omega_s}{\omega_s} \approx \sqrt{\frac{0.52k_s}{(n_i^p - n_i^s)^2L^2} + \left(\frac{\alpha_s - \alpha_i}{\alpha_p - \alpha_i}\right)^2 \sin^2 \Delta \theta_i + \frac{\lambda_i^2}{\lambda_p} \left(\frac{\alpha_p - \alpha_i}{n_i^p - n_i^s}\right)^2 \sin^2 \Delta \theta_p}. \tag{10}
\]

The analogous result for the idler photon can be obtained by interchanging labels $s \leftrightarrow i$.

Equation (10) shows how both the spectral dispersion and spatial dispersion affect the overall spectral width of a down-converted photon. The first term under the radical is the intrinsic bandwidth—that is, the bandwidth determined by spectral dispersion of the phase mismatch in a given emission direction. The second and third terms incorporate the effects of angular broadening of the collection window and pump field, respectively. The coefficient $(\alpha_s - \alpha_i)/(n_i^p - n_i^s)$ in the second term is the rate at which the frequency of peak emission varies with angle. This corresponds to the familiar picture of type-II SPDC, in which the photons are emitted into two sets of concentric cones [18].

As one moves, for example, inward toward the conic axes, the wavelength increases for one photon and decreases for the other. The interpretation of the second term, then, is that increasing the range of accepted angles increases the range of accepted frequencies. The third term under the radical depends on the angular width of the pump and is responsible for the effect observed in our experiment. As previously noted, focusing the pump broadens the angular distribution of the down-converted photons; thus, cones of different color begin to overlap. Whereas a particular collection system might collect photons from only a single “color cone” when the pump is collimated, that same system will “see” adjacent color cones as they are broadened by the effect of the focused pump. Focusing the pump therefore increases the bandwidth, and

\[
A(k_{\perp s},k_{\perp i},\Omega) \approx \exp\left(-\frac{\left((k_{\perp s} + k_{\perp i})/K_p\right)^2}{\frac{L^2}{4} \Delta k_i^2}\right).
\] (5)

We now ask, what is the spectrum of signal or idler photons collected incoherently over some range $\Delta \theta_i$ of emission angles? (Similar results can be obtained for the case that the photons are coherently projected onto a pair of spatial modes, such as the single-mode fibers in our experiment.) For simplicity we consider a pair of spatial masks with Gaussian transmittance function
\[
F(k_{\perp}) = \exp\left[-(k_{\perp}/K_{\perp})^2\right],
\] (6)
where $K_{\perp} = (\omega/c) \sin \Delta \theta_i$. Because we are interested in the single-photon spectra, and not the coincidence spectrum, the mask is applied to only one photon. Accordingly, the spectrum of the collected signal photon is
\[
S(\Omega) = \int \left|F(k_{\perp s})^2 A(k_{\perp s},k_{\perp i},\Omega)^2 \right| dk_{\perp s}dk_{\perp i},
\] (7)
\[
= \int \exp\left[-\frac{L^2}{2} \left(\frac{n_i^p - n_i^s}{c} \Omega_s + \frac{\alpha_s - \alpha_i}{\alpha_p - \alpha_i} k_{\perp s} + \frac{(\alpha_p - \alpha_i) k_{\perp i}}{\bar{L}^2}\right)^2 \right] \left|\frac{k_{\perp s}}{k_{\perp i}}\right| \left|\frac{k_{\perp s} + k_{\perp i}}{K_p}\right| \left|\frac{k_{\perp s}}{k_{\perp i}}\right| dk_{\perp s}dk_{\perp i},
\] (8)
\[
= \exp\left(-2 \frac{\Omega_s^2}{\Delta \omega_s^2}\right),
\] (9)
where

\[
\frac{\Delta \omega_s}{\omega_s} \approx \sqrt{\frac{0.52k_s}{(n_i^p - n_i^s)^2L^2} + \left(\frac{\alpha_s - \alpha_i}{\alpha_p - \alpha_i}\right)^2 \sin^2 \Delta \theta_i + \frac{\lambda_i^2}{\lambda_p} \left(\frac{\alpha_p - \alpha_i}{n_i^p - n_i^s}\right)^2 \sin^2 \Delta \theta_p}. \tag{10}
\]
For a range of pump waists, the two-photon amplitude, Eq. (3), was calculated exactly (using all orders of the dispersion) and projected onto a Gaussian fiber mode of angular width 4 mrad for either the ordinary or extraordinary photon. The resulting distribution was then squared and integrated over the emission angle of the second photon to yield the spectral density of the first photon. The resulting spectra were fit to Gaussian functions, whose widths are plotted as solid lines in Fig. 3. As can be seen, the prediction of the model is in good agreement with the experimental data. The measured spectral widths have little uncertainty as they are obtained from fits to interferograms. The most significant uncertainty in the data (shown as horizontal error bars in Fig. 3) is in the angular width of the pump beam as determined by measuring the waist size of the pump beam. This uncertainty, estimated to range from about 20% at weak focusing conditions to about 30% at strong focusing, arises from imprecision in locating the beam waist and from power fluctuations during the knife-edge measurements of the beam diameter.

In summary, we have observed and modeled spectral asymmetries in cw-pumped type-II spontaneous parametric down-conversion. As the pump beam is focused, both ordinary and extraordinary photons experience spectral broadening. But in contrast to the type-I case, the effect is stronger for one polarization than the other. A simple theoretical model and detailed numerical simulations indicate that such an asymmetry can be attributed to the difference in the angular dispersion (walk-off) of the two kinds of photons, coupled with the well-known correlation between wavelength and emission direction. These conditions are present in several common SPDC schemes, including the now commonplace technique initially reported in [12]. The effect is not observed, however, when the pump is weakly focused, in periodically poled materials where walk-off is nonexistent or in type-I SPDC where the signal and idler experience identical walk-offs.

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