

Spectral properties of entangled photon pairs generated via frequency-degenerate type-I spontaneous parametric down-conversion

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We report the complete measurement of the spectral properties of entangled photon pairs generated via frequency-degenerate type-I spontaneous parametric down-conversion pumped by a cw laser in both the collinear and the noncollinear regimes. The measurement includes the single-photon spectra as well as the two-photon joint spectra. Our results reveal interesting yet subtle differences between the collinear and the noncollinear regimes of frequency-degenerate type-I spontaneous parametric down-conversion. The single-photon and two-photon spectral measurements are in good agreement with the numerical simulation taking into account the tuning curve and the experimental geometry.

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I. INTRODUCTION

An efficient source of entangled photons is one of the most essential resources for experimental research in quantum information [1], quantum metrology [2,3], quantum imaging [4,5], etc. At present, there exist a number of entangled photon generation schemes including, spontaneous parametric down-conversion (SPDC) in a noncentrosymmetric crystal [6,7], spontaneous four-wave mixing (SFWM) in an optical fiber [8,9], in a photonic crystal fiber [10], and in a silicon waveguide [11,12], and the biexciton decay process in a semiconductor quantum dot [13,14].

By far, SPDC has proven to be the most versatile source of entangled photon pairs, exhibiting two-photon quantum entanglement in various photonic degrees of freedom, including, polarization [15,16], position-momentum [5], phase-momentum [17], energy-time [18], time-bin [19], and spectra [20]. Due to the phase-matching condition, the SPDC photon pairs are inherently entangled in position-momentum [21] and in spectra [22,23]. Entanglement in other photonic degrees of freedom can be engineered by exploiting the inherent position momentum and spectral entanglement of the SPDC photon pairs and by making use of two-photon quantum interference phenomena [23–26].

The spectral properties of the SPDC photon pairs are especially important as they are strongly coupled to the Shih-Alley and Hong-Ou-Mandel-type two-photon quantum interference effect [15,27], which is at the heart of many quantum-information and quantum-metrology applications of entangled photons [22,23,28,29]. Complete understanding of the spectral properties of the entangled photon pairs generated via the SPDC process, therefore, is an essential step toward developing engineered two-photon entangled states [23,25].

Type-II SPDC has been of particular importance in generation of polarization entangled photons since Ref. [16]. It has been shown that the degree of polarization entanglement in type-II SPDC is intricately related to the two-photon joint

spectral properties of the photon pair, which may be engineered by judiciously selecting the pump and the crystal parameters [22,28]. Recently, experimental mapping of the type-II two-photon joint spectrum function was reported in literature [20,30,31].

Type-I SPDC is also a major entangled photon source, demonstrating entanglement in a variety of photonic degrees of freedom [32–38]. Since photon pairs generated in the type-I SPDC process normally have much broader spectral bandwidths than those of type-II SPDC photon pairs, the single- and the two-photon joint spectral properties of type-I SPDC could significantly affect entanglement in other photonic degrees of freedom of the photon pair. It is, thus, of importance and interest to study the complete spectral properties of the type-I SPDC photon pair. In this paper, we report experimental and theoretical studies on the single-photon spectra and the two-photon joint spectral properties of the entangled photon pair generated via frequency-degenerate type-I SPDC pumped by a cw uv laser in both the collinear and the noncollinear regimes.

II. SPECTRAL PROPERTIES OF TYPE-I SPDC

In type-I SPDC, the pump photon is spontaneously split into a pair of daughter photons of the same polarization in a noncentrosymmetric crystal. This process must satisfy the so-called phase-matching conditions,

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_p,$$

$$\omega_1 + \omega_2 = \omega_p,$$

which in fact are the momentum conservation condition and the energy conservation condition, respectively. Here $\vec{k}$ is the wave vector of the photon and ω is the frequency of the photon. The subscripts 1, 2, and p , refer to the signal, the idler, and the pump photon, respectively.

The phase matching, however, cannot be perfect in real experimental situations due to dispersion and the finite thickness of the nonlinear crystal. Therefore, the real phase-matching condition always contains the phase-mismatch term Δ and it is precisely the phase-mismatch term that gives

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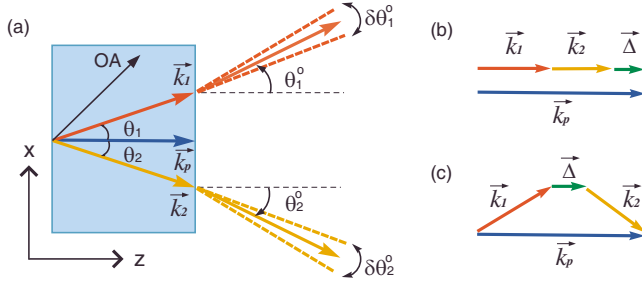


FIG. 1. (Color online) (a) Type-I phase-matching condition. OA is the optic axis. $\delta\theta_1^o$ and $\delta\theta_2^o$ are the collection angles of the signal and the idler photons, respectively. (b) Collinear phase matching, and (c) noncollinear phase matching.

rise to the spectral bandwidth of the SPDC process [39]. Figure 1(a) shows the geometry of the pump, the signal, and the idler photons inside and outside the nonlinear crystal. It also shows the real wave-vector matching conditions for the collinear, Fig. 1(b), and the noncollinear, Fig. 1(c), type-I SPDC, which contain the phase-mismatch term Δ .

The phase mismatch Δ is calculated to be [40]

$$\Delta(\lambda_1, \lambda_2, \theta_1^o) = k_p(\lambda_p, \Psi) - k_1(\lambda_1) \sqrt{1 - \left(\frac{\sin \theta_1^o}{n_o(\lambda_1)} \right)^2} - k_2(\lambda_2) \sqrt{1 - \left(\frac{\lambda_2}{\lambda_1} \right)^2 \left(\frac{\sin \theta_1^o}{n_o(\lambda_2)} \right)^2}, \quad (1)$$

where $k_p(\lambda_p, \Psi) = 2\pi n_{\text{eff}}(\lambda_p, \Psi)/\lambda_p$. Here Ψ and n_{eff} , respectively, are the angle of the optic axis with respect to $\vec{k}_p$ and the effective refractive index of the pump photon.

To see how the phase-mismatch term Δ affects the spectral properties of the entangled two-photon state in type-I SPDC, it is necessary to evaluate the quantum state $|\psi\rangle$ of the photon pair explicitly. It is well known that $|\psi\rangle$ is given by [22,23]

$$|\psi\rangle = C \int \int d\omega_1 d\omega_2 \text{sinc}\left(\frac{\Delta L}{2}\right) \mathcal{E}_p(\omega_1 + \omega_2) a_1^\dagger(\omega_1) a_2^\dagger(\omega_2) |0\rangle, \quad (2)$$

where C is a constant and Δ is the longitudinal phase mismatch as defined in Eq. (1). The envelope of the pump laser is given as $\mathcal{E}_p(\omega_1 + \omega_2)$ as in Ref. [23]. Finally, $a_1^\dagger(\omega_1)$ and $a_2^\dagger(\omega_2)$ are the creation operators for the signal and the idler photons of frequencies ω_1 and ω_2 , respectively.

From Eq. (2), we define the joint spectrum function of the two-photon state as [21,23]

$$S(\lambda_1, \lambda_2, \theta_1^o) = \text{sinc}^2\left(\frac{\Delta(\lambda_1, \lambda_2, \theta_1^o)L}{2}\right), \quad (3)$$

assuming that the pump is a narrow-band cw laser, as is the case in our experiment. Note that, as mentioned in Ref. [39], we have assumed that the pump laser is unfocused. A focused pump beam in type-I SPDC can give rise to a different two-photon joint spectrum function than the one shown in Eq. (3) [41].

The tuning curve or the spectral distribution of the signal and the idler photons as a function of the angle outside the crystal can be evaluated by using Eq. (3) and the energy conservation condition $\lambda_2 = \lambda_1 \lambda_p / (\lambda_1 - \lambda_p)$. The single-photon spectra of the signal and the idler photons can be calculated from Eq. (3) if the emission angles, θ_1^o and θ_2^o , are specified. In frequency-degenerate type-I SPDC, the signal and the idler photons are expected to have the same single-photon spectra because the two photons are completely identical in polarization and in the emission angles.

The two-photon joint spectral distribution can also be calculated from Eq. (3). In Ref. [20], the two-photon joint spectra was calculated for type-II SPDC without considering the effect of collection angles. The experimental results and the theoretical prediction, however, agreed well. In this paper, we consider the finite collection angles of the experimental geometry to calculate the theoretical two-photon joint spectra since the bandwidth and the angular spread of type-I SPDC are much broader than those of type-II SPDC.

The theoretical two-photon joint spectra are evaluated as follows. First, we define the collection angles $\delta\theta_1^o$ and $\delta\theta_2^o$ about the mean emission angles θ_1^o and θ_2^o of the signal and the idler photons, respectively, as shown in Fig. 1. These angles are determined by the experimental geometry, most notably, the locations and the openings of the irises used in the experimental setup.

Second, we define the scanning ranges of the wavelength λ_1 of the signal photon. Then, for a specific value of λ_1 , we determine the emission angle θ_1^o of the signal photon within the collection angle $\delta\theta_1^o$. By using these two initial values λ_1 and θ_1^o , the energy conservation condition $\lambda_2 = \lambda_1 \lambda_p / (\lambda_1 - \lambda_p)$, and the transverse phase-matching condition $k_1(\lambda_1) \sin \theta_1^o / n_o(\lambda_1) = k_2(\lambda_2) \sin \theta_2^o / n_o(\lambda_2)$ [39], it is possible to evaluate the wavelength λ_2 and the corresponding emission angle θ_2^o of the conjugate idler photon.

Finally, we compare if the calculated θ_2^o falls within the predetermined collection angle (by the experimental geometry) of the idler photon $\delta\theta_2^o$. These steps are repeated for all possible ranges of λ_1 and θ_1^o and only the solutions that fall within the predetermined collection angles $\delta\theta_1^o$ and $\delta\theta_2^o$ are kept. The plot of Eq. (3) as functions of both λ_1 and λ_2 evaluated above then becomes the theoretically calculated two-photon joint spectrum for type-I SPDC.

III. COLLINEAR SPDC

In the collinear frequency-degenerate type-I SPDC, the signal and the idler photons have the same central wavelength, $\lambda_1 = \lambda_2 = 2\lambda_p$, and propagate in the same direction as the pump laser beam, see Fig. 1(b), so that $\theta_1^o = \theta_2^o = 0$. The collinear type-I SPDC has shown to be important in building a high-quality source of polarization entangled photon pairs in the ultrafast pumping condition [33].

The experimental setup to measure the single-photon spectra and the two-photon joint spectra is shown in Fig. 2. A 2-mm-thick type-I BBO crystal is pumped by a 351.1 nm argon ion laser, generating collinearly propagating degenerate photon pairs centered at 702.2 nm. The pump beam is then reflected by two pump blocking mirrors. Two auxiliary

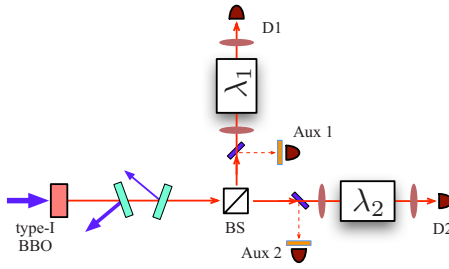


FIG. 2. (Color online) Experimental setup for measuring the single-photon and the two-photon joint spectra of collinear frequency-degenerate type-I SPDC. Aux 1 and Aux 2 are auxiliary detectors used for alignment. λ_1 (Oriel, CS260) and λ_2 (CVI, DK480) are monochromators.

single-photon detectors Aux 1 and Aux 2, each equipped with narrow-band interference filters at 702.2 nm, are used for tuning the BBO crystal for collinear degenerate SPDC. Once the crystal is properly tuned, the mirrors in front of the auxiliary detectors are flipped down and the SPDC photons are sent to the monochromators λ_1 (Oriel, CS260) and λ_2 (CVI, DK480).

Figure 3 (left-hand side) shows the calculated tuning curve for collinear degenerate type-I SPDC centered at 702.2 nm generated from a 2-mm-thick BBO. The optic axis angle in this case is $\Psi=33.5^\circ$. It clearly shows that collinear degenerate type-I SPDC has very broad single-photon spectrum. The thick vertical line at the center represents the collection angle of 0.1° used in the experiment. Figure 3 (right-hand side) shows the calculated single-photon spectrum for the present experimental condition. The full bandwidth is roughly calculated to be 80 nm.

The experimentally measured single-photon spectra are shown in Fig. 4. The single-photon spectra are, as expected, centered at the degenerate wavelength of 702.2 nm and have very large bandwidths which agree well with the calculated value shown in Fig. 3. The decrease of the count rate toward the longer wavelengths shown in the measured single-photon spectra (Fig. 4) is caused by the strong wavelength-dependency of the efficiencies of the monochromator gratings [42,43].

The coincidence measurements shown in Fig. 4 are measured, for example, by scanning the settings of the monochromator for D1 while the monochromator for D2 is fixed

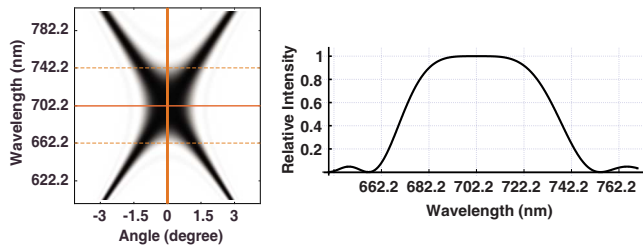


FIG. 3. (Color online) Left-hand side: Calculated tuning curve for collinear degenerate type-I SPDC centered at 702.2 nm, generated from a 2-mm-thick BBO at $\Psi=33.5^\circ$. The thick vertical line in the tuning curve represents the collection angle of 0.1° used in our experiment. Right-hand side: The calculated single-photon spectrum for the present experimental conditions.

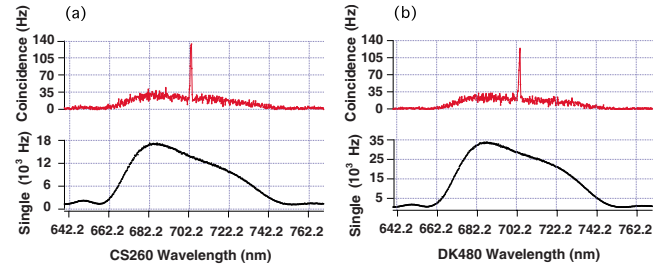


FIG. 4. (Color online) Experimentally measured single-photon spectra. (a) The single-photon spectrum observed at D1. (b) The single-photon spectrum observed at D2. For the coincidence measurement, the monochromator, CS260 or DK480, is scanned while the monochromator for the conjugate photon, DK480 or CS260, is fixed at 702.2 nm, acting as a narrow-band filter.

at 702.2 nm setting, acting as a narrow-band filter. The coincidence measurements clearly demonstrate the conjugate nature of the signal and the idler photons in the spectral domain as a single sharp peak at 702.2 nm. Note that slight increase of the coincidence counts around the 702.2 nm peak is caused by the increased accidental coincidences, which in fact comes from the single-count distributions.

The two-photon joint spectrum for collinear degenerate type-I SPDC is obtained by recording the coincidence counts between the detectors D1 and D2 while scanning the wavelength settings of both monochromators λ_1 and λ_2 . The experimentally obtained two-photon joint spectrum is shown in Fig. 5(a) [44]. The data show that there exists strong negative frequency correlation between the photon pair for the very large bandwidth.

The numerically calculated two-photon joint spectrum for the present experimental condition is shown in Fig. 5(b). Here, the collection angles are assumed to be $\delta\theta_1=\delta\theta_2=0.1^\circ$. It is evident that the experimental data and the numerical simulation agree quite well.

Note that the two-photon joint spectrum projected onto λ_1 (CS260) or λ_2 (DK480) axes should give the single-photon spectrum of the signal or the idler photons. This is due to the fact that, in the entangled two-photon system described by the density matrix ρ , the properties of the signal (or the idler) photon is determined by the partial trace over the unobserved system, i.e., $\rho_s=\text{Tr}_i[\rho]$ [45]. Since the two-photon joint spectrum shown in Fig. 5 is nearly antisymmetric, the projection

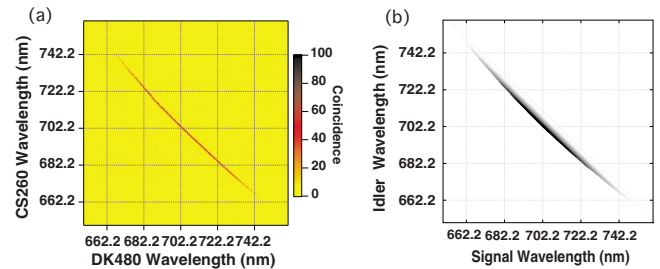


FIG. 5. (Color online) (a) Experimentally obtained two-photon joint spectrum for collinear degenerate type-I SPDC. The accumulation time is 2 s and accidental coincidences have been subtracted [44]. (b) Numerically calculated two-photon joint spectrum for $\delta\theta_1=\delta\theta_2=0.1^\circ$ agrees well with the experimental data.

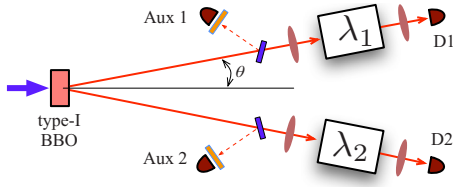


FIG. 6. (Color online) Experimental setup for measuring the spectral properties of noncollinear degenerate type-I SPDC. The angle θ between the pump (351.1 nm) and the signal and idler photons (702.2 nm) is 3° . Aux 1 and Aux 2 are auxiliary detectors.

would lead to nearly identical single-photon spectra for the signal and the idler photons, as evidenced in the experimental data shown in Fig. 4.

IV. NONCOLLINEAR SPDC

In the noncollinear frequency-degenerate type-I SPDC, the signal and the idler photons propagate by making an angle θ with respect to the pump beam, see Fig. 1(c). The noncollinear type-I SPDC scheme was used in one of the first experimental demonstrations on the photon pair generation via SPDC [7] and the polarization entanglement of the photon pair in the SPDC process was first demonstrated using this scheme [15]. The noncollinear degenerate type-I SPDC continues to play an important role as the efficient entangled photon source for experimental research in quantum information [32].

Figure 6 shows the experimental schematic for measuring the single-photon spectra and the two-photon joint spectrum of noncollinear frequency-degenerate type-I SPDC. A 2-mm-thick type-I BBO crystal is pumped by a 351.1 nm argon ion laser and the 702.2 nm signal and the idler photons make the angle $\theta=3^\circ$ with respect to the pump beam. (The crystal optic axis makes the angle $\Psi=33.9^\circ$ with the pump laser.) Similarly to the collinear case, Aux 1 and Aux 2 are auxiliary detectors used for fine-tuning the nonlinear crystal for the noncollinear SPDC phase-matching condition. Once the desired phase-matching condition is achieved, the mirrors in front of the auxiliary detectors are flipped down and the SPDC photons are sent to the monochromators λ_1 (Oriel, CS260) and λ_2 (CVI, DK480).

We first measured the single-photon spectra observed at the detectors D1 and D2 while scanning the wavelength settings of the monochromators λ_1 and λ_2 . The experimental data for the single-photon spectral measurements are shown in Fig. 7 and they exhibit a few interesting properties. First, the single-photon spectra for the signal and the idler photons are not centered at the degenerate wavelength of 702.2 nm. Second, the coincidence measurements which are performed by scanning the monochromator CS260 or DK480 while the monochromator for the conjugate photon DK480 or CS260 is fixed at the degenerate wavelength of 702.2 nm, nevertheless, demonstrate that the degenerate signal-idler photon pair is present at the designed emission angle of 3° as evidenced by a single sharp peak at 702.2 nm. Note that, as before, slight increase of the background coincidence counts is caused by the increased accidental coincidences, which in

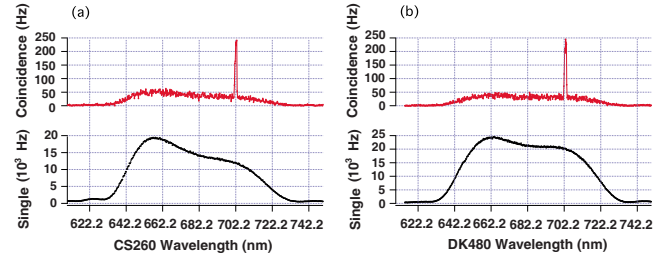


FIG. 7. (Color online) Experimentally measured single-photon spectra of noncollinear degenerate type-I SPDC. (a) The single-photon spectrum observed at D1. (b) The single-photon spectrum observed at D2. The coincidence measurement was performed by scanning the monochromator CS260 or DK480 while the monochromator for the conjugate photon DK480 or CS260 is fixed at the degenerate wavelength of 702.2 nm.

fact comes from the single-count distributions.

The characteristics of the measured single-photon spectra shown in Fig. 7 can be understood by studying the tuning curve of noncollinear frequency-degenerate type-I SPDC which can be calculated from Eq. (3). Figure 8(a) shows the calculated tuning curve for the noncollinear frequency-degenerate type-I SPDC used in this experiment. The left-hand (right-hand) curve in Fig. 8(a) shows the calculated angular spectral distribution of the signal (idler) photon. The single-photon spectrum for the signal or the idler photon is essentially determined by the effective collection angle of the photons in the experimental setup and the two vertical bars at $\pm 3^\circ$ in Fig. 8(a) represent the collection angles $\delta\theta_1'$ and $\delta\theta_2'$ which are defined by the size of the irises.

For example, in Fig. 8(a), it is shown that, while the degenerate photon pair at 702.2 nm may both be collected and contribute to the single-photon spectra, it is not the case for the nondegenerate SPDC photon pair at 662.2 nm (for the signal photon) and 747.3 nm (for the idler photon). Since the 747.3 nm photon is outside the collection angle of the system, only the 662.2 nm photon gets to contribute to the single-photon spectrum.

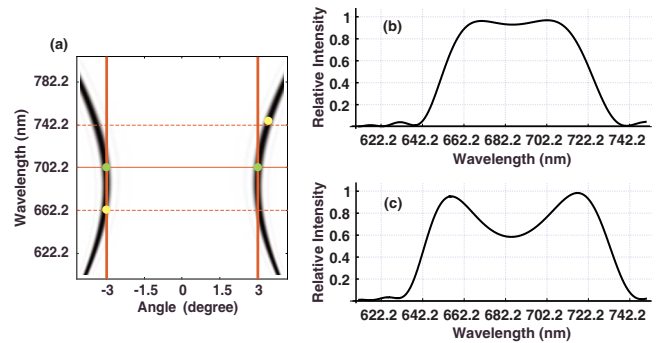


FIG. 8. (Color online) (a) Calculated tuning curve for noncollinear degenerate type-I SPDC at $\Psi=33.9^\circ$. Two vertical bars at $\pm 3^\circ$ represent collection angles $\delta\theta_1'$ and $\delta\theta_2'$ of the experimental setup. While the pair of degenerate photons at 702.2 nm can both be found within the collection angle, it is not the case if the wavelengths of the signal and the idler photons are 662.2 nm and 747.3 nm, respectively. (b) Calculated single-photon spectra for the signal photon at $\theta_1'=2.95^\circ-3.05^\circ$. (c) Calculated single-photon spectra for the signal photon at $\theta_1'=3.01^\circ-3.17^\circ$.

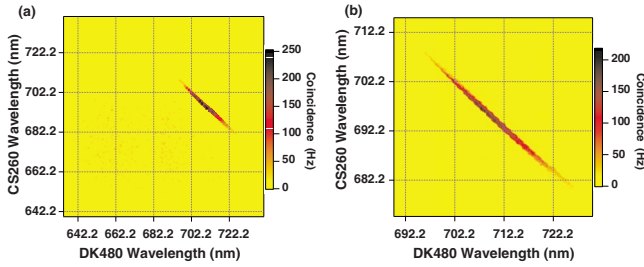


FIG. 9. (Color online) Experimentally measured two-photon joint spectrum for noncollinear degenerate type-I SPDC. (a) and (b) are for the same experimental setup but for different scan ranges and resolution. Accidental coincidences have been subtracted [44].

In Figs. 8(b) and 8(c), we show the theoretically expected single-photon spectra for the collection angles $\theta_1^o = 2.95^\circ - 3.05^\circ$ and $\theta_1^o = 3.01^\circ - 3.17^\circ$, respectively. Indeed, the single-photon spectra are expected to be asymmetric about the degenerate wavelength of 702.2 nm.

Note that the experimentally observed single-photon spectra shown in Fig. 7 are strongly affected by the wavelength-dependent grating efficiency [42,43], it becomes difficult to directly compare the results of numerical simulation, Figs. 8(b) and 8(c), and the measured data, Fig. 7, to accurately estimate the actual collection angles in the experiment. It is, however, evident that the bandwidths of single-photon spectra are not very sensitive to the alignment errors.

Let us now discuss the two-photon joint spectrum of the type-I noncollinear degenerate SPDC. The experimentally observed two-photon joint spectrum is shown in Fig. 9 for the same experimental setup [44]. The experimental data show a much narrower two-photon bandwidth compared to the collinear case studied in Fig. 5. Note also that the two-photon joint spectrum is not centered at the degenerate wavelength of 702.2 nm.

To understand these characteristics, it is necessary to study theoretically expected two-photon joint spectrum, taking into account the effect of the collection angles, following the procedures discussed in Sec. II. In Fig. 10, we show the results of these calculations for two different cases: (a) The signal and the idler photon collection angles are assumed to be the same and symmetric at $\theta_1^o = \theta_2^o = 2.95^\circ - 3.05^\circ$, see Fig. 10(a). (b) The signal and the idler photons are collected at slightly different angles, $\theta_1^o = 2.95^\circ - 3.05^\circ$ and $\theta_2^o = 3.01^\circ - 3.17^\circ$, see Fig. 10(b).

For the case in which the collection angles are symmetric, $\theta_1^o = \theta_2^o = 2.95^\circ - 3.05^\circ$, the theoretical two-photon joint spec-

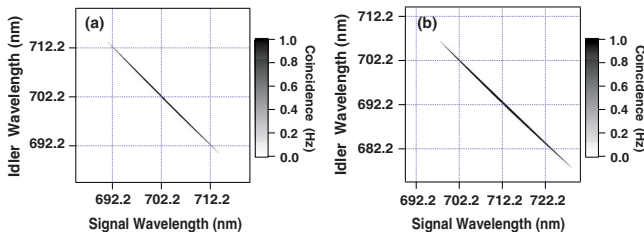


FIG. 10. (Color online) Calculated two-photon joint spectra for noncollinear degenerate type-I SPDC. (a) For $\theta_1^o = \theta_2^o = 2.95^\circ - 3.05^\circ$. (b) For $\theta_1^o = 2.95^\circ - 3.05^\circ$ and $\theta_2^o = 3.01^\circ - 3.17^\circ$.

trum function is found to be, in fact, perfectly anticorrelated and symmetric about the degenerate wavelength of 702.2 nm, see Fig. 10(a). On the other hand, for slightly nonsymmetric collection angles, $\theta_1^o = 2.95^\circ - 3.05^\circ$ and $\theta_2^o = 3.01^\circ - 3.17^\circ$, the theoretical joint spectrum function becomes highly asymmetric about the degenerate wavelength of 702.2 nm, see Fig. 10(b), which is in fact very close to the experimental data shown in Fig. 9(b).

Thus, from Figs. 9 and 10, we can conclude that if the experimental setup was indeed perfectly symmetric, we would have obtained the experimental data that closely resemble Fig. 10(a). However, due to slight errors in the idler photon collection angle, the observed two-photon joint spectrum is greatly modified from the symmetric one. We can also conclude, from these results, that the two-photon joint spectrum of noncollinear frequency-degenerate type-I SPDC is extremely sensitive to the actual collection angles in the experimental setup.

Furthermore, it is interesting to note that the single-photon bandwidths are found to be broad for both the collinear and the noncollinear regimes of frequency-degenerate type-I SPDC, see Figs. 4 and 7. The reduced two-photon bandwidth for noncollinear degenerate type-I SPDC, observed in Figs. 9 and 10, compared to the collinear degenerate type-I SPDC, observed in Fig. 5, can be understood as follows. Consider the tuning curve for noncollinear frequency-degenerate type-I SPDC in Fig. 8(a). Due to the broadband nature of type-I SPDC, there are many nondegenerate photon pairs as well as the degenerate photon pair at the designed emission angles of $\pm 3^\circ$. The small collection angles limit the probability of pair detection if one photon of the photon pair is found to be located outside the collection angle determined by the experimental geometry. Thus, the effective two-photon bandwidth is predominantly determined by the collection angles of the experimental setup in the case of noncollinear frequency-degenerate type-I SPDC. These missing-pair photons, however, do contribute to the single-photon bandwidth, hence broadening the single-photon bandwidth.

Finally, we note that the asymmetry of the single-photon spectra (about the degenerate wavelength of 702.2 nm) in Figs. 7 and 8 is of different origin than the asymmetry of two-photon joint spectrum in Fig. 9. The former comes from the photon pair emission characteristics of noncollinear degenerate type-I SPDC, while the latter is due to experimental alignment errors, albeit very small.

V. CONCLUSION

In this paper, we have reported the complete experimental and theoretical studies on the spectral properties of entangled photon pairs generated from collinear and noncollinear frequency-degenerate type-I SPDC. Our study includes both the single-photon spectra and the two-photon joint spectrum.

For collinear degenerate type-I SPDC, we have found that the single-photon spectra and the two-photon joint spectrum are both very broadband in nature. In addition, the symmetric two-photon joint spectrum showed frequency anticorrelation between the pair photons for broad spectral ranges.

In the case of noncollinear degenerate type-I SPDC, the single-photon spectra showed similar broadband nature but the spectra were not centered at the degenerate wavelength. The two-photon joint spectrum, on the other hand, exhibited much reduced two-photon bandwidth and the experimentally observed two-photon joint spectrum was not symmetric about the degenerate wavelength. We have explained the observation by studying the properties of the noncollinear degenerate type-I SPDC, taking into account the experimental setup, i.e., the collection angles of the photons. We have found that the effective two-photon bandwidth of noncollinear degenerate type-I SPDC is strongly affected and greatly reduced by the limited pair collection angles. As a result, the two-photon joint spectrum for noncollinear degenerate type-I SPDC is extremely sensitive to small alignment errors while the single-photon spectra are not.

The photon pair generation scheme based on noncollinear degenerate type-I SPDC forms the basis for many applications in quantum optics, such as, quantum-information experiments [1], entangled-photon quantum metrology [2,3], quantum imaging [4,5], etc., and the Shih-Alley and Hong-

Ou-Mandel two-photon quantum interference effect is at the heart of these applications [15,27,29]. Since it is the two-photon bandwidth, not the single-photon bandwidth, that is responsible for the Shih-Alley and Hong-Ou-Mandel two-photon dip (the bigger the two-photon bandwidth, the narrower the two-photon dip), it is necessary to use caution in experiments involving the Shih-Alley and Hong-Ou-Mandel two-photon quantum interference effect not to overestimate the effective two-photon bandwidth.

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