Adjusting the properties of the photon generated via an optical parametric oscillator by using a pulse pumped laser*

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(Received 30 March 2011; revised manuscript received 2 June 2011)

The cavity-enhanced spontaneous parametric down-conversion far below threshold can be used to generate a narrow-band photon pair efficiently. Previous experiments on the cavity-enhanced spontaneous parametric down-conversion almost always utilize continuous wave pump light, but the pulse pumped case is rarely reported. One disadvantage of the continuous wave case is that the photon pair is produced randomly within the coherence time of the pump, which limits its application in the quantum information realm. However, a pulse pump can help to solve this problem. In this paper, we theoretically analyze pulse pumped cavity-enhanced spontaneous parametric down-conversion in detail and show how the pump pulse affects the multi-photon interference visibility, two-photon waveform, joint spectrum and spectral brightness.

Keywords: spontaneous parametric down-conversion, photon, pulse pumped, quantum optics

PACS: 42.50.Dv, 42.50.Gy **DOI:** 10.1088/1674-1056/20/11/114206

1. Introduction

A quantum network plays an important role in quantum communication and quantum information processing. In general, a quantum network consists of a storage media and a carrier for transmitting information. A photon can propagate over long distances in free space or in optical fibres and is a robust and efficient candidate for a carrier. Atoms are well-suited for long-lived storage of quantum information in meta-stable states and can be isolated from the environment. The efficient coupling between a photon and an atomic system is a prerequisite for realizing the quantum communication and quantum information processing, which requires that the photon should have a comparable bandwidth with the natural linewidth of an atom. This requirement excludes the common single-photon sources like quantum dots,[1] colour centres,[2] atoms and ions.[3] Currently, the most widely used method for generating single photons or entangled photon pairs is spontaneous parametric down-conversion (SPDC).[4−8] However, due to the wide band of the SPDC photons, typically in the THz range, it is difficult to match the bandwidth of the corresponding atomic system, which is on the MHz scale. Therefore, it is almost impossible to have an efficient coupling between the atom and the photon. This problem can be solved directly with a narrow band filter, but it will reduce the flux of the photons at the same time. Another way is by using an active filtering technique, which is accomplished by placing the down-converted crystal into an optical parametric oscillator (OPO). By using this method, the photons whose frequency matches the cavity mode will be enhanced significantly. Ou and Lu[9] realized the cavity-enhanced SPDC experiment first with a type-I phase-matched crystal, where signal and idler photons were of the same polarization and produced photon pairs with enhanced generation rate and narrow bandwidth. Wang *et al.* obtained a single-photon source with 21 MHz bandwidth by utilizing a similar idea but a different setup,[10−12] where a small diode laser and a periodical poled nonlinear crystal were used, and the wavelength of the generated photon corresponds to the D2 line of Rb atom. Other realizations using a type-II phase-matched setup have been performed and also show properties of narrow bandwidth and high spectral brightness.[13−15]

*Project supported by the National Natural Science Foundation of China (Grant No. 10874171), the National Basic Research Program of China (Grant No. 2009CB929601), the Innovation Fund from Chinese Academy of Sciences, and the Program for New Century Excellent Talents in University of China (Grant No. NCET-07-0791).

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Previous experiments on cavity-enhanced SPDC almost used continuous wave (CW) pump light, but rarely had the reports on pulse-pumped cavity-enhanced SPDC. One disadvantage of the CW pump case is that the photon pair is produced randomly and uncertainly within the coherence time of the pump. In contrast, when a pulse pump is employed, the creation of the down-converted photons only happens in the pump duration, so the pump pulse can act as a gate signal for the production of a photon pair. This would allow synchronization between the photon source and the driving field,[16] and make many quantum protocols possible in practice. In addition, the waveform of the SPDC photon can be controlled by a pump pulse, this means that we can generate a suitable pulse waveform to fit some special requirements, for example, the need of the atomic quantum memory. Therefore, the pulse-pumped cavity-enhanced SPDC attracts people's attention gradually.

In this paper, we will address issues on the influence of pump pulse upon cavity-enhanced SPDC. The outline of the paper is as follows. In Section 2, we figure out how the different pump bandwidth affects the visibility of multi-photon interference. In Section 3, we show how the wave packet of cavity-enhanced SPDC can be manipulated by adjusting the pump light. In Section 4, we calculate the spectral brightness of the SPDC source as a function of pump bandwidth. Finally, we give a very brief conclusion in Section 5.

2. Frequency-uncorrelated photons and visibility of multi-photon interference

As for CW-pumped cavity-enhanced SPDC, a pump photon will split into a signal photon and an idler photon with certain probability. The energy conversation is satisfied among these three photons $\omega_{\rm s}+\omega_{\rm i}=\omega_{\rm p}$, where $\omega_{\rm s(i,p)}$ is the frequency of the signal (idler, pump) photon. The frequencies of the signal photon and idler photon are anti-correlated. This frequency anti-correlation will reduce the distinguishability of the photons and lower the visibility in multi-photon interference,[17] and make many protocols such as quantum teleportation, swapping and generation of a multi-photon non-classical state impossible. This is unfavourable for quantum information processing. In order to overcome this problem, a pulse pump is preferred and by this manner, the frequency anti-correlation between photons in a pair can be eliminated. This kind of frequency uncorrelated entangled photon source can be used to realize the protocols mentioned above. In what follows, we figure out the visibility of multi-photon interference and show the influence of the pump bandwidth on it. We employ two different pump pulse shapes and find that the different shape has different influence on the visibility of multi-photon interference. The two-photon wave function is given by

$$\psi(\omega_1,\omega_2)\propto\frac{1}{(\omega_1-\omega_0)+{\rm i}\frac{\gamma}{2}}\frac{1}{(\omega_2-\omega_0)+{\rm i}\frac{\gamma}{2}}\times\phi(\omega_1+\omega_2){\rm sinc}(\Delta kL/2),\qquad(1)$$

where $1/(\omega_{1,2}-\omega_0+{\rm i}\gamma/2)$ represents the spectrum response function of the cavity with bandwidth γ, $\omega_{1,2}$ are the frequencies of signal and idler respectively, ω_0 is the central frequency of the cavity, $\phi(\omega_1+\omega_2)$ is the frequency spectrum of the pump pulse, Δk means the wave vector mismatching and L is the length of the crystal. Using the theory in Ref. [18], we find that the visibility in multi-photon interference takes the form $V=\varepsilon/(2\kappa+\varepsilon)\propto\varepsilon/\kappa$, where ε and κ are defined as

$$\kappa=\int{\rm d}\omega_1{\rm d}\omega_1'{\rm d}\omega_2{\rm d}\omega_2'\psi(\omega_1,\omega_2)\psi(\omega_1',\omega_2')\psi^*(\omega_1,\omega_2)\times\psi^*(\omega_1',\omega_2'),$$

$$\varepsilon=\int{\rm d}\omega_1{\rm d}\omega_1'{\rm d}\omega_2{\rm d}\omega_2'\psi(\omega_1,\omega_2)\psi(\omega_1',\omega_2')\psi^*(\omega_1,\omega_2')\times\psi^*(\omega_1',\omega_2).$$

According to Schwarz inequality, $\varepsilon/\kappa\leq1$. When the equality holds, the frequencies of two photons are fully uncorrelated, and the wave function in Eq. (1) is able to be factorized into $\phi(\omega_1)\phi(\omega_2)$. The visibility V is related to the bandwidth and the shape of the pump pulse. For example, for a Gaussian pump pulse with bandwidth σ, $\varepsilon/\kappa=0.970$, 0.940 and 0.800 for $\sigma=12.5$ MHz, 8 MHz and 3.7 MHz respectively;[17] while for a rectangular pump pulse, $\varepsilon/\kappa=0.997$, 0.992 and 0.970 for $\sigma=12.5$ MHz, 8 MHz and 3.7 MHz respectively. In both cases, the visibility rises with the increase of the pump bandwidth. The difference in visibility between these two pulses with the same bandwidth is that the transform limit is not identical. Since the coherence time of rectangular pulse is longer, the visibility of multi-photon interference is higher. Based on the results above, we are able to use a pump pulse with congenial bandwidth and shape to generate pure entangled photons. In Ref. [17], the photon pair is generated by using a pump bandwidth

$\sigma = 12.5$ MHz, because the frequency anti-correlation is almost fully eliminated in that case.

3. The two-photon wave function and the waveform of single photon

In recent years, generating a photon with controllable waveform is a hot topic in quantum communication and quantum information processing.[19] For example, in quantum memory, photons stored in atomic media are expected to be retrieved with the highest efficiency, which requires a special waveform of the photon.[20] Hence, controllable waveforms of photons are desirable. Up to now, it has been demonstrated that the waveforms of both single photons and the entangled photons can be manipulated or shaped by some technique. For single photons, the waveforms can be manipulated by an external modulator.[21] The narrow band entangled pairs used are generated by four-wave-mixing (FWM) in an atomic system, Stokes photon is used to trigger a function generator which drives an electro-optic modulator to modulate the wave function of the anti-Stokes photon and the measured coincidence rate $R(\tau) = |\psi(t_{\rm s}, t_{\rm as})|^2$ reveals the information of the waveform, where $\psi(t_{\rm s}, t_{\rm as})$ is the wave function of the photon pair. For entangled photons, two-photon wave packet is commonly shaped in frequency domain.[22−24] Du *et al.*[25] provide a method for shaping the two-photon wave function in time domain by manipulating two input pump fields, where the entangled photons are also generated by means of FWM based on a Λ-type EIT atomic system. By this way, two pump field profiles have been mapped into the two-photon wave packet in time domain. Unfortunately, concerning traditional SPDC, although the pump waveform has an influence on correlation and down-converted photon profile, it cannot be mapped into the two-photon wave packet, so we cannot control the two photon waveform in time domain.[26]

By comparison, in a cavity-enhanced SPDC configuration, the OPO cavity will shape the two-photon wave function in frequency domain, and the input pump profile will be mapped into the two-photon wave packet in time domain, which is different from traditional SPDC. We will show the detailed calculation in what follows. Assuming that only signal field is resonant in the cavity, in this case, we can write the two-photon wave function as

$$\psi(\omega_1, \omega_2) \propto \frac{1}{(\omega_1 - \omega_0) + \mathrm{i}\frac{\gamma_1}{2}} \times \phi(\omega_1 + \omega_2)\mathrm{sinc}(\Delta k L/2). \quad (2)$$

In time domain, the wave function is changed into

$$\Phi(t_1, t_2) \propto \iint_{-\infty}^{+\infty} \mathrm{d}\omega_1 \mathrm{d}\omega_2 \psi(\omega_1, \omega_2) \times \exp(-\mathrm{i}\omega_1 t_1 - \mathrm{i}\omega_2 t_2). \quad (3)$$

We model the pump pulse as a Gaussian pulse, $\phi(\omega) = \exp(-\omega^2/4\Gamma)$, where Γ is the bandwidth of pump pulse. Evaluating the integral in Eq. (3), we obtain

$$\Phi(t_1, t_2) \propto E(t_2) \int \exp[-(t_1 - t_2)\omega_1] \times \mathrm{erf}\left[\frac{1}{10}(50\mathrm{i}t_2 + \omega_1 + \omega_2)\right] \times \frac{1}{\frac{\gamma}{2}\mathrm{i} + \omega_1}\mathrm{d}\omega_1. \quad (4)$$

The error function erf above approximates 1, then Eq. (4) reduces to

$$\Phi(t_1, t_2) \propto E(t_2) \exp\left[-\frac{\gamma}{2}(t_1 - t_2)\right], \quad (5)$$

where $E(t_2) = E_0 \exp(-\Gamma t_2^2)$ is the inverse Fourier transformation of input Gaussian pump pulse in frequency domain. From Eq. (5), we can clearly see that the pump pulse profile has been mapped into the two-photon wave function. This offers a possible way to shape the two-photon waveform in time domain. A similar result is obtained in Ref. [27], where an additional function $\theta(t_1 - t_2)$ is introduced directly in two-photon wave function as a result of delay output of resonant signal light.

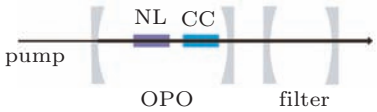


Fig. 1. (colour online) Schematic set-up of a type-II phase-matched cavity-enhanced SPDC. The NL is the parametric down-converted crystal and CC is a crystal for compensation; the filter acts as a passive filtering cavity.

With regard to the waveform of the single photon from the cavity-enhanced SPDC, we shall first treat the OPO cavity as a Lorentzian frequency filter. As shown in Fig. 1, the OPO cavity filters the spectrum of pump pulse and a passive filter cavity is used to realize the single-mode operation. Both the spectral function of the OPO and filter cavity with bandwidth γ take the form

$$S(\omega) \propto \frac{\gamma}{\gamma^2 + \omega^2}.$$

For a pump pulse with waveform $A_{\rm p}(t)$, we find that the output field $A_{\rm i,s}(t)$ from the OPO cavity is related to the input pulse $A_{\rm p}(t)$ by

$$A_{\rm s,i}(t) \propto A_{\rm p}(t) \otimes S(t) = \int_{-\infty}^{t} A_{\rm p}(\tau) S(t-\tau) {\rm d}\tau, \quad (6)$$

where $S(t)$ is the time-domain response of the product of the spectral function of the OPO and the filter cavity.[16] Considering a rectangular input pump pulse, we illustrate the output down-converted pulse waveform from the OPO cavity in Fig. 2. As shown in Fig. 2(b), in virtue of the filtering of the OPO, the signal pulse or idler pulse is widened in time domain and the photon waveform changes but takes the waveform of pump pulse.[28]

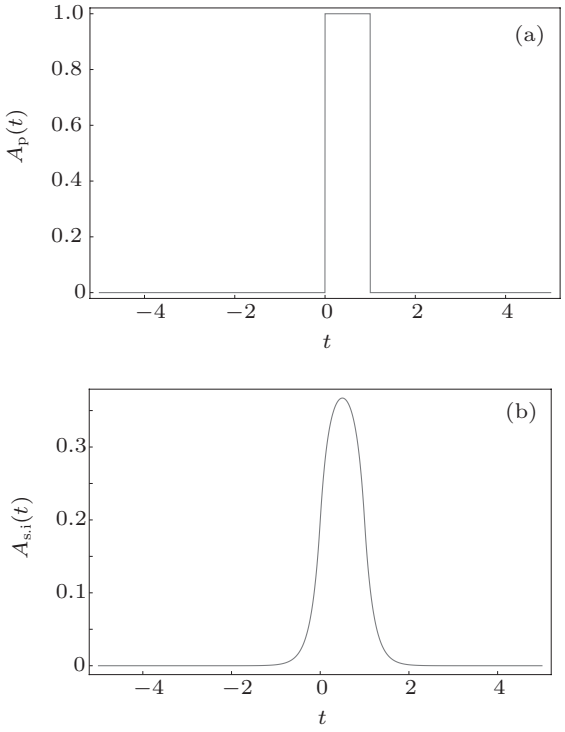


Fig. 2. The waveform of the down-converted photon generated from an OPO cavity: (a) a rectangular pump pulse with 1 ns duration, (b) output photon waveform. The bandwidth of the OPO cavity is 5 MHz.

4. Spectral brightness (biphoton generation rate)

In this section, we discuss in detail about the spectral brightness in different SPDC cases. We start with the SPDC without cavity. The spectral brightness can be calculated by $\rho \propto \langle\psi|\psi\rangle/\sigma$,[29] where σ is the bandwidth of pump pulse, $|\psi\rangle$ is a two-photon state and

$$|\psi\rangle = g \iint {\rm d}\omega_1 {\rm d}\omega_2 E(\omega_1+\omega_2) \times \int_0^L \exp({\rm i}\Delta k z){\rm d}z \, |\omega_1\rangle \, |\omega_2\rangle \, . \quad (7)$$

In Eq. (7), g is a constant, $E(\omega_1+\omega_2) = \exp[-(\omega_1+\omega_2)^2/2\sigma^2]$ is the spectral function of a Gaussian pump pulse, $\int_0^L \exp(i\Delta k z){\rm d}z$ expresses the phase matching function, Δk is the wave vector mismatching and L is the crystal length. The spectral brightness can be expressed as

$$\rho \propto \frac{1}{\sigma} |g|^2 \iint {\rm d}\omega_1 {\rm d}\omega_2 \, |C(\omega_1,\omega_2)|^2 \times |E(\omega_1+\omega_2){\rm sinc}(\Delta k L/2)|^2 \, , \quad (8)$$

where $C(\omega_1,\omega_2)$ is a slowly varying function, we can ignore it in the integral. The term $|E(\omega_1+\omega_2){\rm sinc}(\Delta k L/2)|^2$ is defined as the joint spectrum function, which is the possible distribution of the signal and idler light in the frequency space,[30] and we put it to a clear and plain form in comparison with other expressions.[29] The $|{\rm sinc}(\Delta k L/2)|^2$ is a phase matching term.

Figure 3 shows the phase matching term of a type-Π SPDC with a 6-mm-BBO crystal pumped by

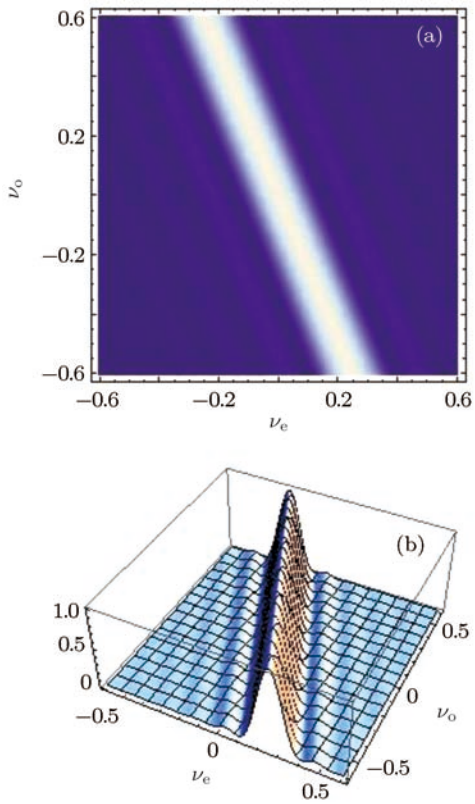


Fig. 3. (colour online) Phase matching function: (a) two dimensional distribution, (b) three-dimensional distribution. The pump pulse wavelength is centred at 425 nm with 2-nm bandwidth. The crystal is BBO and the length is 6 mm.

a 425-nm laser. Figures 3(a) and 3(b) are a two-dimensional and a three-dimensional simulation respectively. The values at the two plane coordinate axes $\nu_{\rm e,o} = \nu_{\rm i,s}/\nu_{\rm cw}$ represent normalization frequencies of the signal and idler light respectively, where $\nu_{\rm i,s} = \omega_{\rm i,s} - \omega_{\rm i,s}^{(0)}$, $\omega_{\rm i,s}^{(0)}$ is the central frequencies of the signal and idler light; $\nu_{\rm cw} = 2.78/\left|k_{\rm i}' - k_{\rm s}'\right| L$ is the bandwidth of down-conversion with CW pump in Ref. [31], where $k_j' = \partial k_j(\omega)/\partial(\omega)\Big|_{\omega=\omega_j^0}, j = {\rm s, i}$. From these two figures, we can clearly observe that the phase matching term is asymmetric.

We calculate the joint spectrum which is visualized in Fig. 4, the bandwidth of the pump laser changes from 2 nm to 5 nm to 10 nm. It is very remarkable that the joint spectrum becomes more asymmetric with the increase of the pump bandwidth.

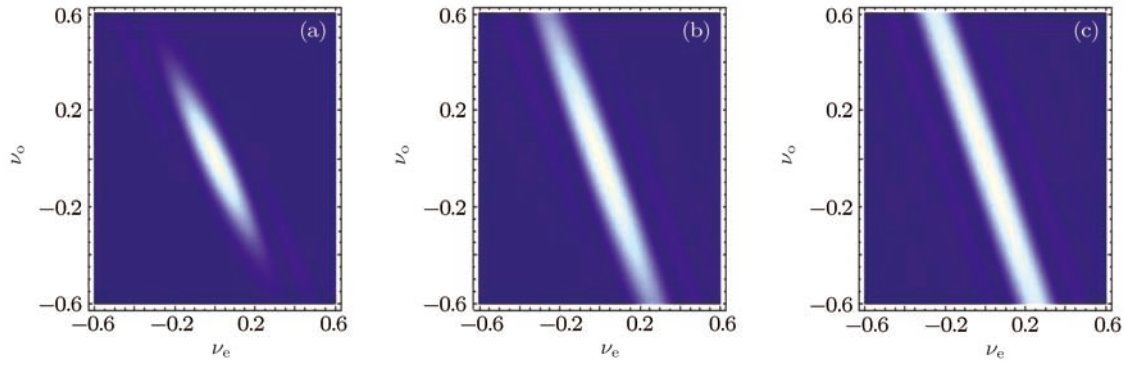


Fig. 4. (colour online) Stimulated joint spectrum of a type-II SPDC without cavity. The bandwidth of the pump changes from (a) 2 nm to (b) 5 nm to (c) 10 nm.

With the joint spectrum function, evaluating the spectral brightness via Eq. (8) is possible. The simulation result is shown in Fig. 5. We find that the pump pulse bandwidth has no impact on the spectral brightness for SPDC when the bandwidth of the pump is larger than the phase matching bandwidth (about 0.35×10^{14} rad/s), which is similar to the result obtained in Ref. [29]. The difference is that when the pump bandwidth is smaller than that of the phase matching, the spectral brightness becomes smaller with the decrease of the pump bandwidth. The result is reasonable because when the pump bandwidth in calculation is smaller than the bandwidth of phase matching function, the spectral brightness is mainly decided by the pump pulse. With the decrease of the bandwidth, the peak power of the pump laser drops gradually and the nonlinear efficiency falls correspondingly. Therefore, the spectral brightness (or biphoton generation rate) becomes smaller.

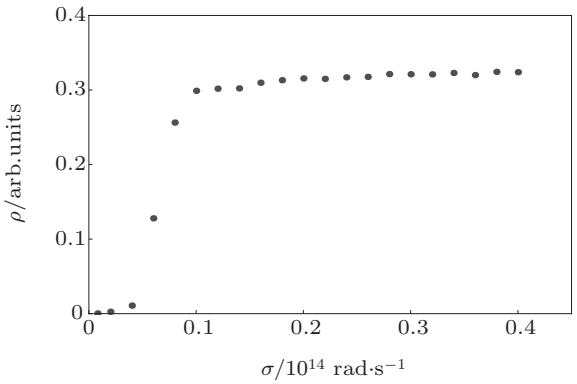


Fig. 5. Simulated source spectral brightness as a function of pump bandwidth. The spectral brightness shows no dependence on the pump bandwidth when the pump bandwidth is larger than the bandwidth of the phase matching. When the pump bandwidth is much smaller than that of the phase matching term, the spectral brightness reduces with the decrease of the pump bandwidth.

In the case of cavity-enhanced SPDC, the calculation of spectral brightness is similar to that given above for SPDC without cavity. Considering that both the signal and idler light are resonant together, we can calcuate the spectral brightness as

$$\rho \propto \frac{1}{\sigma}\left|g\right|^2 \iint {\rm d}\omega_1 {\rm d}\omega_2 \frac{\gamma}{\omega_1^2 + (\frac{\gamma}{2})^2}\frac{\gamma}{\omega_2^2 + (\frac{\gamma}{2})^2} \times \left|C(\omega_1,\omega_2)\right|^2 \left|E(\omega_1+\omega_2){\rm sinc}(\Delta k L/2)\right|^2 . \quad (9)$$

The modified joint spectrum becomes

$$\frac{\gamma}{\omega_1^2 + (\frac{\gamma}{2})^2}\frac{\gamma}{\omega_2^2 + (\frac{\gamma}{2})^2}\left|E(\omega_1+\omega_2){\rm sinc}(\Delta k L/2)\right|^2 .$$

For an OPO cavity with 5-MHz bandwidth, the joint spectrum distribution is plotted in Fig. 6(b). It is illustrated that because of the filtering effect of the OPO cavity, the distribution range is much smaller than that in the case of SPDC without cavity. In Fig. 6(a),

the joint spectrum distribution in the case of the single resonance is shown for comparison. We discover that the joint spectrum is only shaped along ν_o axis by the OPO cavity. Figure 6(c) shows the zoom of the Fig. 6(b). We calculate the spectral brightness based on the joint spectrum function and the result is shown in Fig. 7. The graph clearly demonstrates that with the decrease of pump bandwidth, the spectral brightness of photon pairs is improved. This is because that the narrower the pump bandwidth is, the higher the pulse energy density is and the more photon number in one cavity mode is. Therefore, the spectral brightness increases. When the pump bandwidth and the OPO bandwidth are of the same order of magnitude, most of the pump energy is coupled into the cavity mode and the spectral brightness will be higher. Here, we only take into consideration the biphoton spectral brightness. In the case that single photon spectral brightness is desired, we only need to integrate the double resonant joint spectrum function over idler (signal) frequency. The following calculation is exactly the same.

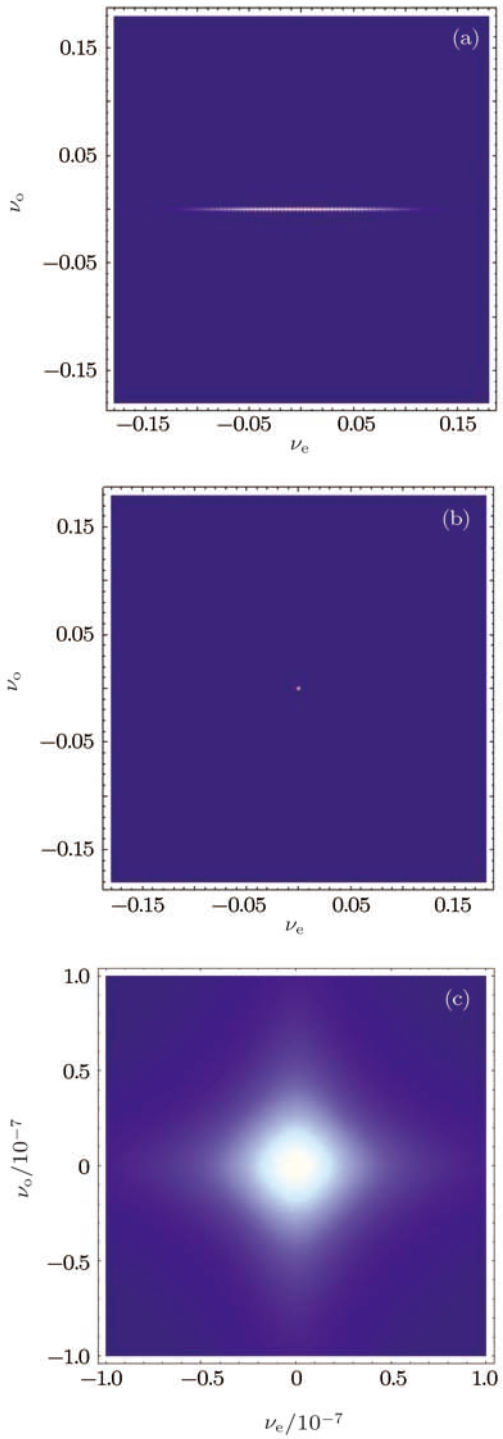


Fig. 6. (colour online) Simulated joint spectrum of a cavity-enhanced SPDC: (a) single-resonant case, (b) double-resonant case, (c) zoom of (b). The bandwidth of the OPO cavity is 5 MHz.

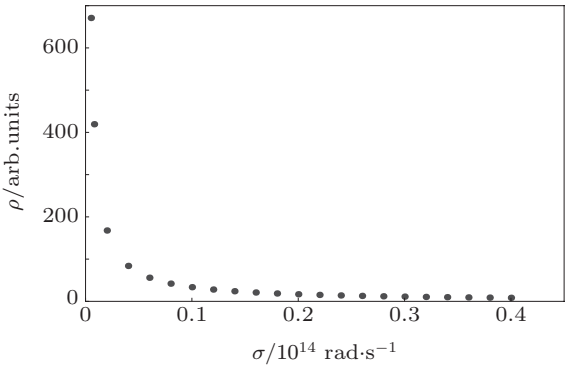


Fig. 7. Spectral brightness of double resonant cavity-enhanced SPDC versus the pump bandwidth.

In the cavity-enhanced SPDC, the biphoton generation rate or spectral brightness is not only related to the pump bandwidth, but also related to the cavity finesse and crystal itself. Because the resonant enhancement factor is proportional to the square of finesse,[9] the photon generation rate or spectrum brightness can be improved by increasing the cavity finesse. Since the finesse is mainly determined by the reflectivity of coupling output mirror, we can also figure out down-converted pulse intensity as a function of reflectivity of coupling output mirror. According to Fig. 8, the output field leaves the cavity with length L after numerous bounces with $E_t = E_i t_2/(1 - r_2 e^{i\varphi})$, where E_i is the input pump field, t_2 is the transmittivity of the output coupling mirror while r_2 is the reflectivity and φ means the round-trip phase shift. The ratio of the transmitted intensity to the input pump intensity gives $I_t/I_i = |t_2|^2/(1-r_2 e^{-i\varphi} - r_2 e^{i\varphi} + r_2^2)$. On resonance, $I_t/I_i = |t_2|^2/(1-r_2)^2$ and a mathematical simplification leads to the intensity enhancement

factor $B = I_t/I_i = (1 + r_2)/(1 - r_2)$.

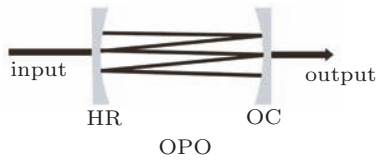


Fig. 8. The simplified OPO resonant cavity setup. HR: high reflecting mirror; OC: output coupling mirror.

Figure 9 shows the dependence of transmitted pulse intensity on reflectivity of the output coupling mirror r_2. With the increase of reflectivity, the transmitted pulse intensity, which is proportional to the number of photon pairs, is improved. Therefore, the generation rate can be improved. It is especially pronounced when r_2 is larger than 80%. In addition, choosing an efficient crystal will also improve the photon generation rate, for example, a periodically poled crystal, which owns a large nonlinear coefficient and much longer useful length, can further lead to a higher photon yield.

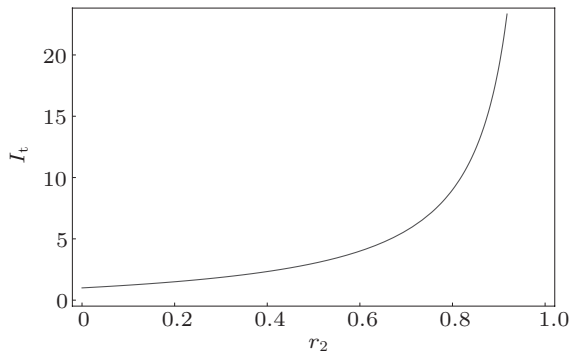


Fig. 9. Transmitted pulse intensity versus output coupling mirror reflectivity r_2.

5. Conclusion

We have discussed the pulse pumped cavity-enhanced SPDC. The core is how the bandwidth of the pump affects the properties of the generated photon, especially on the joint spectrum, spectral brightness, etc. A clear and plain joint spectrum was presented and it made the figure of spectral brightness more effective. Our results show that the important properties of the generated photon can be easily adjusted by simply changing the bandwidth of the pump pulse. We have also made a comparison between the case of cavity-enhanced SPDC and the case without a cavity, and some interesting differences are analysed. We believe our results are very beneficial to the research in this direction.

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