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Research Paper

Photon pair sources with controlled frequency correlation

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ABSTRACT

Development of efficient and well-controlled nonclassical photon sources is one of the keys in the quantum information and communication technology. We present our recent activities to develop advanced sources of photon pairs having controlled frequency correlation, by use of quasi-phase matching (QPM) and extended phase-matching (EPM). First, we present the generation of polarization and frequency entangled photons using QPM having two poling periods. We also demonstrate the photon pair generation with controlled frequency correlation and its application to making heralded single photons with intrinsically pure spectrotemporal modes.

KEYWORDS

quantum information, quantum optics, entanglement, quasi-phase matching, extended phase matching

1 Introduction

In the development of quantum information and communication technology (QICT), there are many technical issues to be solved. Development of efficient sources of entanglement is one of such essential keys toward the QICT. Photons are the most popular and powerful method to generate and distribute the entanglement [1]. Especially, spontaneous parametric down-conversion (SPDC) is frequently used to generate entangled photons in many poof-of-principle experiments. Quasi-phase matching (QPM) using periodically poled nonlinear crystals is a powerful technique to extend the applicability of nonlinear wavelength conversion including SPDC [2]. Recently, extended phase matching (EPM) also attracts attention in the entangled photon generation [3]. Such new techniques are very useful not only in the entanglement generation but also in the generation of spectrally pure single photons heralded by their sister photons [4], [5]. For instance, the linear optical quantum computing [6] and the measurement-based quantum computing [7], [8] require large number of photons that are essentially indistinguishable from each other, to carry out linear quantum gate operations and to prepare large-scale cluster states. Control of frequency correlation between photons is one of the key issues to achieve efficient generation of photon pairs that satisfy the required conditions. Here we present our recent results on the generation of photon pairs having controlled frequency correlation by use of QPM and EPM in SPDC.

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2 Entangled photon generation using two-period QPM-SPDC

SPDC is a nonlinear optical process in which a pump light is converted into two (signal and idler) lights in a crystal with $\chi^{(2)}$ optical nonlinearity. From a quantum optical point of view, SPDC is a process in which twin daughter photons are produced simultaneously from a parent photon. In this process, the phase matching conditions must be fulfilled:

$$\omega_p = \omega_s + \omega_i, \tag{1}$$

$$k_p = k_s + k_i, \tag{2}$$

where $\omega_{p,s,i}$ and $k_{p,s,i}$ are the frequencies and wave vectors of the pump (p), signal (s), and idler (i) photons, respectively. These conditions are regarded as energy and momentum conservations of the photons concerned. As a result, the signal and idler photons have natural correlations in energy and momentum. SPDC using a natural optical nonlinear crystal has limitation in its working wavelength and efficiency because the phase matching condition depends on the natural dispersion of birefringence. QPM is the technique that compensates a deviated phase matching condition with the help of periodic modulation of the nonlinear susceptibility $\chi^{(2)}$. In ferroelectric crystals such as $LiNbO_3$, $\chi^{(2)}$ can be modulated by periodic domain inversion, i.e., periodic poling. Thus, the phase matching condition (2) can be controlled by the poling period Λ as

$$k_p = k_s + k_i + m\frac{2\pi}{\Lambda}, \ (m : \text{integer}). \tag{3}$$

Periodically poled $LiNbO_3$ (PPLN) is the most major device used for QPM. In particular, QPM-SPDC in PPLN waveguides are used for the efficient generation of entangled photons in the telecom wavelength region [2], [9], aiming at applying to quantum cryptography.

Figure 1 shows the tuning curves for type-II SPDC in PPLN as a function of the poling period at 120.0°C, calculated using the Sellmeier equations [10], [11]. The type-II SPDC emits a pair of daughter photons with orthogonal polarizations, i.e, ordinary (o) and extraordinary (e) rays. The solid and dashed curves in Fig. 1 are the tuning curves for the o-ray and e-ray, respectively. Here, we use the configuration where o-ray and e-ray have horizontal (H) and vertical (V) polarizations, respectively. As shown in the figure, when Λ=9.25 μm, the e-ray at 1510 nm and the o-ray at 1590 nm are emitted. On the contrary, when Λ=9.5 μm, the o-ray at 1510 nm and the e-ray at 1590 nm are emitted. Therefore, the superposed emission from the two poling periods can generate non-degenerate (two-color) photon pairs in the polarization-entangled state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{H}\rangle_1|\mathrm{V}\rangle_2 + e^{i\phi}|\mathrm{V}\rangle_1|\mathrm{H}\rangle_2\right), \tag{4}$$

where $|\mathrm{H}\rangle_i$ and $|\mathrm{V}\rangle_i$ represent the states for horizontal and vertical polarizations of each photon, respectively.

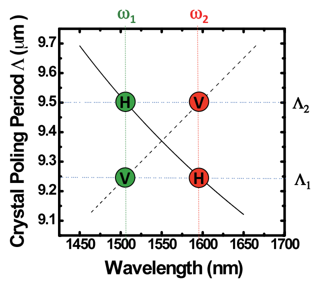

Fig. 1 Calculated tuning curve of the type-II QPM-SPDC in PPLN at 120.0°C. The wavelength of the pump light is λp = 775 nm.

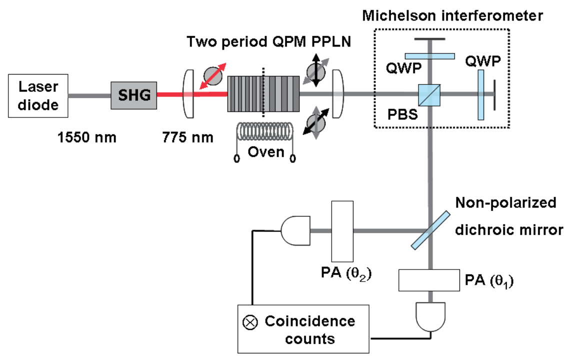

Fig. 2 Experimental setup for polarization correlation measurement of the photon pairs.

The state (4) is one of the maximally entangled states. Here, the subscripts 1 and 2 denote the photon states with wavelengths at 1510 and 1590 nm, respectively. The phase difference ϕ between the two terms in (4) originates from the difference in the chromatic dispersion of the birefringent crystal for the two orthogonally polarized photons having non-degenerate frequencies. This phase difference can be controlled as described later. Since the wavelengths of photons in a pair are different from each other, one can separate the pair in a deterministic way by, for instance, using a dichroic mirror.

The experimental setup to observe the polarization-entangled photons is shown in Fig. 2. A PPLN crystal (40 mm long and 0.5 mm thick) having two poling periods was fabricated by the full-cover electrode method [12]. To produce SPDC, the crystal was pumped by the pulses at 775 nm, which is the second harmonic of an amplified external cavity laser diode. The pulse width, repetition rate, and average power of the pump were 2.5 ns, 4 MHz, and 9 mW, respectively. The crystal was kept at 120.0°C where the emission spectra generated from the two poling periods were observed to be identical having the center wavelengths at 1510 nm and 1590 nm. A polarization-devision Michelson interferome-

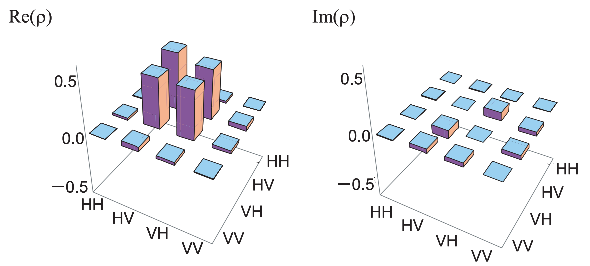

Fig. 3 Real and imaginary parts of the reconstructed density matrix ρ of the two-photon polarization state.

ter compensates the group velocity difference between the photons having perpendicular polarizations. It also controls the phase difference between the two terms in (4); the phase difference $\Delta\phi$ added by the interferometer is $\Delta\phi = (\omega_1 - \omega_2)\Delta L/c$, where ΔL is the path-length difference in the interferometer. Each photon split by a dichroic mirror (DM) was passed through a polarization analyzer (PA), which consists of a quarter wave plate, a half wave plate and a polarizing beam splitter. The photon was then detected by a single photon detector based on an InGaAs/InP avalanche photodiode. The coincidence signal between the two detectors was collected for various polarization combinations, which were governed by the two PAs.

From the polarization correlation measurements, we reconstructed the density matrix of the two-photon polarization state [13], [14]. Figure 3 shows the density matrix ρ we thus obtained [15]. Here, the phase in (4) was set to be $\phi = 0$; the expected state was

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}} (|\mathrm{H}\rangle_1|\mathrm{V}\rangle_2 + |\mathrm{V}\rangle_1|\mathrm{H}\rangle_2) . \tag{5}$$

The fidelity F of the reconstructed density matrix ρ to the ideal Bell state (5) was $F = \langle\Psi^+|\rho|\Psi^+\rangle = 0.94$, indicating that the generated state was close to the ideal Bell state.

Our photon pair source also produces frequency-entangled state

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left(|\omega_1\rangle_\mathrm{H}|\omega_2\rangle_\mathrm{V} + e^{i\phi}|\omega_2\rangle_\mathrm{H}|\omega_1\rangle_\mathrm{V}\right) \tag{6}$$

when we divide the photons in terms of their polarization. The phase ϕ is the same as that in (4) and is controlled by the interferometer as described above. In this case, the non-degenerate Hong-Ou-Mandel (ND-HOM) interference [16] exhibits the beat-note fringes expressed by $1 - \cos\phi$. The fringe visibility reflects the coherence between the two terms in the state (6), and thus manifests the frequency entanglement. To observe the ND-HOM interference, we replaced the dichroic mirror in Fig. 2 with a polarized beamsplitter

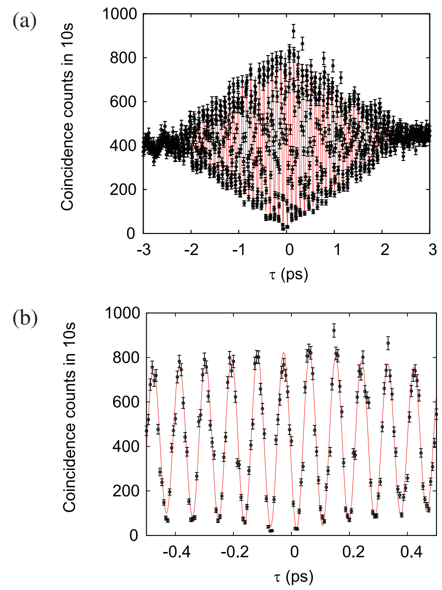

Fig. 4 Observed ND-HOM interference as a function of $\tau = \Delta L/c$. Figure (b) is the enlarged view of (a) around $\tau \sim 0$.

(PBS) preceded by a half wave plate to divide the photons in terms of $\pm 45°$ polarizations. The observed ND-HOM interference (Fig. 4) [17] exhibited the high visibility (93.4 ± 1.9 %) fringes, indicating that the photon pair is in the frequency-entangled state (6). The envelope of the fringe visibility shown in Fig. 4 (a) reflects the temporal overlap between the photon wave packets. We note that the photon pair state (6) generated by this method can be regarded as a state having controlled frequency correlation in the two discrete frequencies, i.e., two frequency bins.

3 Controlled frequency correlation using EPM

In usual phase matching methods including QPM, the phase matching only at a certain frequency is taken into account. To control the spectrotemporal properties of the twin photons generated by SPDC, one must consider the deviation of the phase matching condition around the frequency concerned. The technique is called as EPM. Assume that the phase matching condition (2) or (3) is fulfilled at ω_s, ω_i and $\omega_p = \omega_s + \omega_i$ and that the pump, signal, and idler photons propagate collinearly. Define the wavenumber deviation Δk from the phase-matching condition as a function of ω_s and ω_i as

$$\begin{aligned}\Delta k(\omega_s, \omega_i) &= k_s(\omega_s) + k_i(\omega_i) \\ &\quad - k_p(\omega_s + \omega_i) + m\frac{2\pi}{\Lambda}.\end{aligned} \tag{7}$$

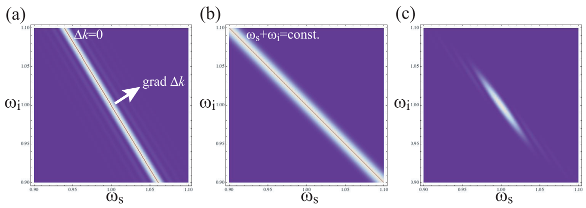

Fig. 5 Example of (a) phase-matching function *f*, (b) pump spectrum *g*, and (c) joint spectral distribution *fg*.

The photon flux of the SPDC is proportional to the phase-matching function

$$f = \left(\frac{\sin \Delta k L/2}{\Delta k/2}\right)^2, \tag{8}$$

where L is the crystal length. Figure 5 (a) is the example of the two-dimensional density plot of f as a function of ω_s and ω_i. The ridge of f exhibits the direction along which the phase-matching condition $\Delta k = 0$ is fulfilled. The direction perpendicular to the ridge is expressed by the direction of the gradient

$$\begin{aligned} \text{grad } \Delta k &= \left(\frac{\partial \Delta k}{\partial \omega_s}, \frac{\partial \Delta k}{\partial \omega_i}\right) \\ &= \Big(v_g^{-1}(\omega_s) - v_g^{-1}(\omega_p), \\ &\qquad v_g^{-1}(\omega_i) - v_g^{-1}(\omega_p)\Big). \end{aligned} \tag{9}$$

Here, $v_g = d\omega/dk$ is the group velocity. Thus, the gradient direction is governed by the dispersion of refractive indices. In addition, the energy conservation condition (1) must be fulfilled in the SPDC. This means that the SPDC flux is also proportional to the power spectrum of the pump beam $g(\omega_p) = g(\omega_s + \omega_i)$, an example of which is shown in Fig. 5 (b). Thus the total SPDC photon flux is proportional to the product of f and g, as shown in Fig. 5 (c). The two-photon state of the SPDC can be expressed by

$$|\Psi\rangle = \iint d\omega_s d\omega_i S(\omega_s, \omega_i)|\omega_s\rangle|\omega_i\rangle. \tag{10}$$

The "joint spectral distribution" fg of the SPDC is proportional to $|S(\omega_s, \omega_i)|^2$.

Here, we consider the three special cases:

(i) $v_g^{-1}(\omega_s) = v_g^{-1}(\omega_i)$,

(ii) $v_g^{-1}(\omega_s) + v_g^{-1}(\omega_i) = 2v_g^{-1}(\omega_p)$,

(iii) $v_g^{-1}(\omega_s) = v_g^{-1}(\omega_p)$.

In these cases, the ridges of the joint spectral distribution are along −45°, +45°, and 0° in the ω_s–ω_i plane, respectively. In cases (i) and (ii), and in the limit of long crystal, the two-photon state is entangled with anti-correlated and correlated frequencies,

$$|S(\omega_s, \omega_i)| = \delta(\omega_s + \omega_i), \tag{11}$$

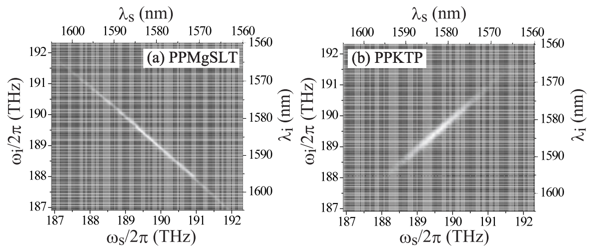

Fig. 6 Measured joint spectral distributions of SPDC generated from (a) PPMgSLT and (b) PPKTP.

$$|S(\omega_s, \omega_i)| = \delta(\omega_s - \omega_i) g^{1/2}(\omega_s + \omega_i), \tag{12}$$

respectively. In case (iii), the two-photon state is a product (separable) state with no frequency correlation

$$|S(\omega_s, \omega_i)| = \delta(\omega_i - \omega_0) g^{1/2}(\omega_s + \omega_0), \tag{13}$$

where ω_0 is the center frequency of the idler. This state is useful in the application of heralded single photon generation; the single signal photon heralded by the idler is spectrally pure because of the lack of frequency correlation between the signal and idler photons. In this context, a number of works have been carried out to generate spectrally pure, heralded single photons using SPDC [4], [5], [18] and four-wave mixing in optical fibers [19]–[22].

We have generated and demonstrated the three kinds of two-photon states. For the state in case (i), we used periodically poled MgO-doped stoichiometric $LiTaO_3$ (PPMgSLT) in the type-II QPM condition. For the state in case (ii), we used periodically poled $KTiOPO_4$ (PPKTP) crystal in the type-II QPM. We used a mode-locked Ti:sapphire laser operated in cw mode as a pump source for the PPMgSLT, and in pulsed mode (spectral width: 6 nm, pulse duration: 120 fs) for the PPKTP crystal. The observed joint spectral distributions for PPMgSLT and PPKTP are shown in Fig. 6 (a) and (b), respectively [23]. We see that the two-photon spectra exhibit the frequency anti-correlation (11) and correlation (12), as expected.

In case (ii), the widths of the joint spectral distribution along −45° and +45° are governed by the widths of the phase-matching function f and the pump spectrum g, respectively. Thus, we can independently control the widths along the two orthogonal directions. In particular, when the two widths are identical, we can make a circular joint spectral distribution. The SPDC in this case has no spectral correlation between signal and idler photons, providing high spectral purity of each photon and high indistinguishability between photons generated from independent SPDC sources. The photons produced in this way are very useful in generating various quantum states consisting of multiple number

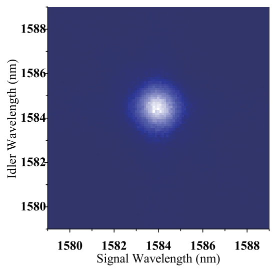

Fig. 7 Joint spectral distribution of SPDC generated from a 30-mm-long PPKTP crystal and 0.4-nm-wide pump pulses.

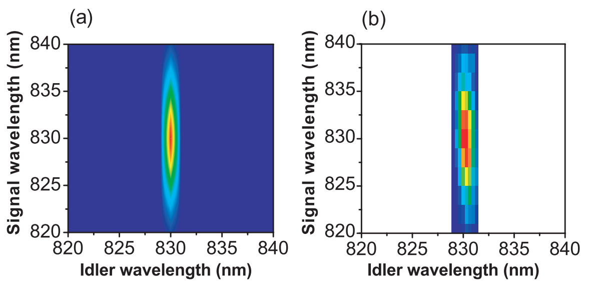

Fig. 8 (a) Calculated and (b) measured joint spectral distributions of SPDC generated from KDP.

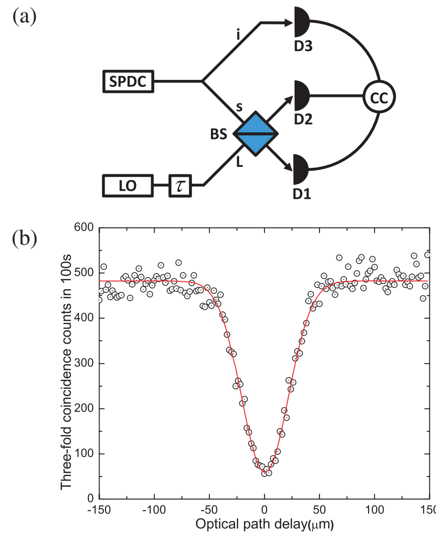

Fig. 9 (a) Sketch of the Hong-Ou-Mandel interference experiment between the signal (s) and coherent (L) photons heralded by the idler (i) photon. Note that the interference was observed upon three-fold coincidence between the signal, idler, and coherent photons. (b) Observed Hong-Ou-Mandel interference.

of photons, since such photons must be indistinguishable with each other. Figure 7 presents the circular-shaped joint spectral distribution thus generated, using a 30-mm-long PPKKTP and 0.4-nm-wide pump pulses (temporal duration: 3 ps) at $\lambda = 792$ nm [24]. We see that the joint spectral distribution has a good circular shape, as expected. It is also noteworthy that the two-photon generation rate (η) of this method was quite high: the observed $\eta = 4.1 \times 10^4\ \mathrm{s^{-1}mW^{-1}}$ are almost one order of magnitude grater than those obtained by existing techniques to produce indistinguishable photon pairs using SPDC.

To generate the state in case (iii), we used KH_2PO_4 (KDP) crystal in type-II QPM pumped at $\lambda = 415$ nm. The resulting SPDC centered at $\lambda = 830$ nm has a joint spectral distribution as in (13) [4], [5]. We used a mode-locked Ti:sapphire laser (spectral width: 7.1 nm, pulse duration: 100 fs) as a pump source. Figures 8 (a) and (b) present the calculated and observed joint spectral distributions, respectively. The observed joint spectral distribution is in good agreement with the calculation, showing the characteristic profile in (13). The Schmidt Value [5] calculated from the joint spectral distribution is 1.03, which ensures high purity of the state. Hong-Ou-Mandel (HOM) interference [25] is a good test to check the indistinguishability between single photons. In fact, Mosley *et al.* demonstrated that the signal (or idler) photons generated from the two independent SPDC sources exhibited the high-visibility HOM interference [4], [5]. Also interesting is that the signal photon thus generated has a pure spectrotemporal mode with a bandwidth that is almost the same as that of the coherent photons generated from the laser source, the second harmonic of which is the pump source of the SPDC. In this context, the signal photon heralded by the idler should also exhibit the HOM interference with a weak coherent light from the laser source [18], [26]. As shown in Fig. 9, we have observed [27] the high-visibility HOM interference manifesting the high spectral purity of the signal photon that is indistinguishable from the coherent photons. The observed visibility 89.4 ± 0.5 % was the highest in the HOM interference between single and coherent photons ever reported without spectral filtering [18], [26]. We also note that our pure, heralded single photon source is much more efficient than those employing spectral filtering [26]. Thus, our heralded single photon source will be useful in generating multiple photons necessary for various experiments in multi-qubit QICT. Also, its ability of high-visibility interference with coherent photons is promising for the new hybrid QICT protocols that combine discrete photon optics and continuous-variable optical techniques, e.g., homodyne detection.

4 SUMMARY

We have demonstrated the generation of polarization and frequency entangled photons using two-period

QPM. Also demonstrated are the photon pair generation with controlled frequency correlation by use of EPM. These techniques are to be powerful tools in the development of advanced QICT.

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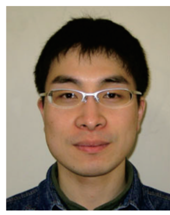

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