Generation of polarization-entangled photon pairs via concurrent spontaneous parametric downconversions in a single $\chi^{(2)}$ nonlinear photonic crystal

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We propose a scheme for generating polarization-entangled photon pairs using a $\chi^{(2)}$ nonlinear photonic crystal, which is designed for enabling two concurrent quasi-phase-matched spontaneous parametric downconversion processes. Beamlike photon pairs produced from each process are collinear but noncollinear with the pump. Moreover, the source we design works in a postselection-free way and applies to both degenerate and nondegenerate cases. Combining possible waveguide technologies, our scheme may provide an integrated polarization entanglement source.

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Polarization-entangled photons are widely used in testing quantum mechanics foundations [1] and various photonic quantum technologies [2]. Spontaneous parametric downconversion (SPDC) is a conventional way to generate such entanglement, typically using the type-II birefringence phase-matching in a nonlinear crystal [3] or two type-I crystals [4]. However, such sources emit photons in a cone-like way, and generally only a small fraction of the cone is collected for use. Thus, such sources are less efficient.

SPDC based on quasi-phase-matching (QPM) materials with the second-order nonlinear susceptibility $\chi^{(2)}$ modulated is a more efficient and flexible way to produce photonic quantum states. Moreover, QPM SPDC usually emits photon pairs in a collinear and beamlike configuration, thus leading more efficient collection. A postselected polarization entanglement source was first realized by separating collinear orthogonally polarized photon pairs produced by type-II QPM SPDC with a beam splitter [5]. However, this method suffers a 50% loss and its applications are limited by the postselection measurement. Numerous schemes have been reported to build postselection-free polarization entanglement sources. A widely used method is coherently combining photon pairs from two QPM SPDCs via interferometers [6,7] or more compactly through QPM structure engineering [8–11]. In this Letter, we present a new postselection-free, beamlike, polarization entanglement source based on a $\chi^{(2)}$ nonlinear photonic crystal (NPC), which is designed to provide QPM conditions for two concurrent SPDCs. Our scheme can work in both degenerate and nondegenerate cases.

The $\chi^{(2)}$ NPC, namely the two-dimensional (2D) QPM material, has attracted much interest since first introduced by Berger [12], as it can provide flexible multiple-beam or multiple-frequency nonlinear processes [13–15]. Here we design an NPC structure as shown in Fig. 1(a), where circularly inverted domains (with $-\chi^{(2)}$) distribute hexagonally on a $+\chi^{(2)}$ background with a period of Λ. Figure 1(b) illustrates its reciprocal lattice, and the reciprocal vectors $\vec{G}_{m,n} = m\vec{e}_1 + n\vec{e}_2$, the amplitude of which can be expressed as

$$|\vec{G}_{m,n}| = \frac{4\pi}{\sqrt{3}\Lambda}\sqrt{m^2+n^2+mn}, \tag{1}$$

where m, n are integers. If the crystal size is considered infinitely large, the nonlinear susceptibility $\chi^{(2)}$ can be written as a Fourier series [12],

$$\chi^{(2)}(\vec{r}) = d\sum_{m,n}\mathcal{G}_{m,n}e^{-i\vec{G}_{m,n}\cdot\vec{r}}, \tag{2}$$

where d is the effective nonlinear coefficient and $\vec{r} = (y, z)$ is the 2D spatial coordinate. The Fourier coefficients $\mathcal{G}_{m,n}$ depend on the first order Bessel functions,

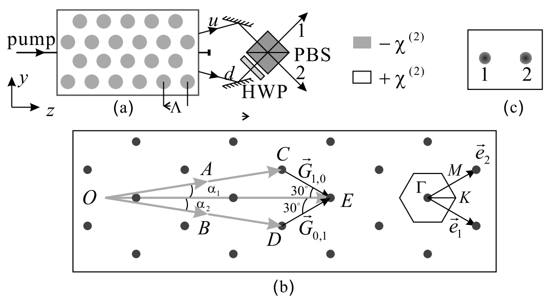

Fig. 1. (a) Schematic of polarization entanglement generation using a hexagonal inverted domain $\chi^{(2)}$ NPC. Lowercase letters and numbers label the beams. PBS, polarizing beam splitter; HWP, half-wave plate set at 45°. (b) Reciprocal lattice of the crystal. Thick grey arrows represent pump, signal, and idler wave vectors. Thin black arrows represent reciprocal vectors. The first Brillouin zone with the usual Γ, M, and K points is represented on the right. (c) Transverse pattern of the parametric light in the Fourier plane.

$$\mathcal{G}_{m,n} = \frac{2R}{\Lambda\sqrt{m^2+n^2+mn}} J_1\left(\frac{4\pi R}{\sqrt{3}\Lambda}\sqrt{m^2+n^2+mn}\right), \quad (3)$$

where R is the radius of the circularly inverted domain and R/Λ is called duty cycle.

We consider the pump wave vector in the z direction, which is along ΓK direction in the first Brillouin zone. We set horizontal (H) and vertical (V) polarization parallel and perpendicular to the y-z plane, respectively. For the desired frequencies we may design the crystal to satisfy two concurrent type-II QPM conditions,

$$\Delta k_1 = \vec{k}_{p,H}^{\overrightarrow{OE}} - \vec{k}_{s,H}^{\overrightarrow{OA}} - \vec{k}_{i,H}^{\overrightarrow{AC}} - \vec{G}_{1,0}^{\overrightarrow{CE}} = 0, \quad (4)$$

$$\Delta k_2 = \vec{k}_{p,H}^{\overrightarrow{OE}} - \vec{k}_{s,H}^{\overrightarrow{OB}} - \vec{k}_{i,V}^{\overrightarrow{BD}} - \vec{G}_{0,1}^{\overrightarrow{DE}} = 0, \quad (5)$$

where p, s, i represent the pump, signal, idler fields, respectively, and the superscripts represent the vectors shown in Fig. 1(b). From Eqs. (1) and (3) we obtain

$$|\vec{G}_{1,0}| = |\vec{G}_{0,1}| = \frac{4\pi}{\sqrt{3}\Lambda}, \qquad \mathcal{G}_{1,0} = \mathcal{G}_{0,1} = \frac{2R}{\Lambda} J_1\left(\frac{4\pi R}{\sqrt{3}\Lambda}\right). \quad (6)$$

We can numerically find the approximate maximum value of $\mathcal{G}_{1,0}$ is 0.344 when $R/\Lambda \approx 0.33$. The angle between parametric and pump beams can be calculated as

$$\alpha = \arcsin \frac{|\vec{G}_{1,0}|}{2(|\vec{k}_{s,H}| + |\vec{k}_{i,V}|)}. \quad (7)$$

This angle can be used to build classical probe lights for aligning the following setup.

If we consider a classical continuous-wave (cw) plane-wave pump with horizontal polarization, by applying analogy calculations made in [10] we can obtain the SPDC output state up to two-photon term as

$$|\Psi\rangle = |\mathrm{vac}\rangle + A\int \mathrm{d}\nu \Phi(\nu)[|H(\Omega_s+\nu)\rangle_u |V(\Omega_i-\nu)\rangle_u + |H(\Omega_s+\nu)\rangle_d |V(\Omega_i-\nu)\rangle_d] + \cdots, \quad (8)$$

where we have assumed the crystal is large enough in y direction and neglected the transverse distribution of wave vectors, leaving only the ideal QPM wave vectors along vectors $\overrightarrow{OA}$ and $\overrightarrow{OB}$ denoted by the subscripts u and d, respectively. Ω_s and Ω_i are central frequencies of signal and idler photons, respectively, which are supposed to satisfy the perfect QPM conditions given by Eqs. (4) and (5) and the energy-conservation condition $\Omega_s + \Omega_i = \omega_p$. The bandwidth of the downconverted light is supposed that deviations from these central frequencies satisfy $|\nu| \ll \Omega_j$, $j = s, i$.

The joint spectrum amplitude $\Phi(\nu)$ is written as

$$\Phi(\nu) = e^{-i\frac{L\Delta k_z}{2}} \mathrm{sinc}\frac{L\Delta k_z}{2}, \quad (9)$$

where L is the crystal length along z direction and $\Delta k_z = k_p - k_s \cos\alpha - k_i \cos\alpha - |\vec{G}_{1,0}|\cos 30°$. By expanding the wave vectors up to the first order in ν, we have

$$\Delta k_z \approx -\nu D \cos\alpha, \qquad D = 1/u_H(\Omega_s) - 1/u_V(\Omega_i), \quad (10)$$

where $u_q(\Omega_j)$ ($j = s, i$, $q = H, V$), are the group velocities at central frequencies. Then we have

$$|\Phi(\nu)|^2 = \mathrm{sinc}^2 \frac{L\nu D \cos\alpha}{2}, \quad (11)$$

corresponding to bandwidth $\Delta\omega \approx 1.77\pi/(LD\cos\alpha)$.

The coefficient A absorbs all the constants and slowly varying functions of frequency, which can be found as

$$A = \frac{iE_p L d \mathcal{G}_{1,0}}{2c}\sqrt{\frac{\Omega_s\Omega_i}{n_{s,H}n_{i,V}}}, \quad (12)$$

where E_p is the electrical field amplitude of pump and $n_{j,q}$, $j = s, i$, $q = H, V$, denote the refraction index of a q-polarized photon at frequency Ω_j.

From the SPDC state given by Eq. (8) we can know the signal and idler photons are generated collinearly but noncollinearly with the pump, and thus we can infer the transverse pattern of the parametric light in the Fourier plane as shown in Fig. 1(c). Therefore, with such a specific NPC, two beam-like SPDC sources are coherently integrated in a single crystal. The underlining physics of this integration is the concurrent multiple QPM conditions resulting from multiple reciprocal vectors.

To obtain polarization entanglement, as shown in Fig. 1(a), we first let either output beam, for instance path mode d, pass a half-wave plate (HWP) oriented at 45°, which induces transformations $|H\rangle \to |V\rangle$, $|V\rangle \to |H\rangle$. Then we make the two beams overlap at a polarizing beam splitter (PBS), which transmits (reflects) horizontally (vertically) polarized photons. The output state after the PBS can be written as

$$|\Psi_{\mathrm{out}}\rangle = A\int \mathrm{d}\nu \Phi(\nu)[|H(\Omega_s+\nu)\rangle_1 |V(\Omega_i-\nu)\rangle_2 + e^{i\varphi}|V(\Omega_s+\nu)\rangle_1 |H(\Omega_i-\nu)\rangle_2], \quad (13)$$

where the subscripts 1 and 2 represent the output path modes of the PBS. The phase φ depends on the path length difference of beams u and d. We can see that the above equation shows a definite maximally polarization-entangled state in both degenerate or nondegenerate cases. This result is based on the ideal crystal structure. For a realistic crystal, to get a high-degree entanglement the crystal structure requires to be approximately symmetry, which can make sure $\mathcal{G}_{1,0} \simeq \mathcal{G}_{0,1}$.

The photon pair generation rate can be estimated by normalizing the state $|\Psi_{\mathrm{out}}\rangle$, given by

$$R = \langle \Psi_{\mathrm{out}} | \Psi_{\mathrm{out}} \rangle = \frac{2\pi d^2 \mathcal{G}_{1,0}^2 L P \Omega_s \Omega_i}{\varepsilon_0 n_p c^3 S n_{s,H} n_{i,V} |D| \cos\alpha}. \quad (14)$$

Here we use $|E_p|^2 = 2P/(\varepsilon_0 n_p c S)$, where P denotes the pump power and S represents the transverse area of the pump beam.

To show the experimental feasibility of our scheme, we design two example structures using the lithium niobate (LN) crystal. The first one enables degenerate QPM for wavelengths $\lambda_p = 775$ nm, $\lambda_s = \lambda_i = 1550$ nm. SPDC sources at such wavelengths have wide applications in long-distance fiber-based quantum information processing. Setting 180°C as working temperature, we get the modulation period $\Lambda = 9.47$ μm and the angle $\alpha = 1.24°$. By setting $P = 1$ mW, $S = 0.05$ mm^2, $L = 5$ mm and using $d = d_{24} \approx 4.6$ pm/V and the maximum $\mathcal{G}_{1,0}$ of 0.344, we can estimate a generation rate of $3.6k$ pairs/s and a bandwidth of 4.4 THz. Note that the crystal length should be much shorter than the noncollinear length given in [16] to suppress the SPDC spatial walk-off effect. The above parameters satisfy this condition. This condition decreases the generation rate compared with the collinear QPM SPDC sources.

The second structure is designed for a nondegenerate QPM SPDC source of $\lambda_p = 532$ nm, $\lambda_s = 810$ nm, $\lambda_i = 1550$ nm. Such a source can meet the requirement in real-world quantum networks, for instance photonic memories in quantum repeaters. Also at a working temperature of 180°C, we obtain $\Lambda = 4.90$ μm and $\alpha = 1.62°$. Similarly, we can get the generation rate as $3.0k$ pairs/s and the bandwidth as 2.0 THz.

Both of the two example structures are within current technologies of engineering QPM structures. Therefore, we conclude that we have proposed a new experimental feasible scheme for generating polarization-entangled photon pairs. The source has several merits. First, our source coherently integrates two QPM SPDCs, opening up a way for integrated photonic source engineering. Although a PBS is required, since no state projection measurement is required at the PBS, thus in a typical linear optical circuit, it can be a part of the subsequent waveguide devices via evanescent wave coupling between two adjacent waveguides, and alternatively, it can combine the following unitary operations into a whole operation. Second, the downconverted photons are generated collinearly but noncollinearly with the pump. Our source preserves the advantage of better collection as a beam-like source, while it does not require the dichroic element for separating the pump light, hence avoiding the contamination from the pump and dispensing with several filters before or after the nonlinear crystal. Thus, it is easier for our source to get better signal-to-noise ratio. Third, our scheme is versatile such that maximal entanglement can be obtained in both degenerate and nondegenerate cases. Fourth, as in ultrafast pulsed SPDC H- and V-polarized photons differ in their spectral widths [17,18], while here we use a HWP to switch the H and V polarization in path d, therefore all the H- and V-polarized photons originally generated from the crystal are output in paths 1 and 2, respectively. This feature may avoid wasting photons in narrowband filters and improve the coincidence count rate in multiphoton interference experiments [19].

Finally, $\chi^{(2)}$ NPC has been widely studied in the classical nonlinear optics community, while we hope our approach may stimulate more investigations on its applications in the quantum optics field.

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