Generation of path-polarization hyperentanglement using quasi-phase-matching in quasi-periodic nonlinear photonic crystal

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Abstract: A compact scheme for the generation of path-polarization entangled photon pairs is proposed by using a quasi-periodic nonlinear photonic crystal to simultaneously accomplish four spontaneous parametric down-conversion processes.

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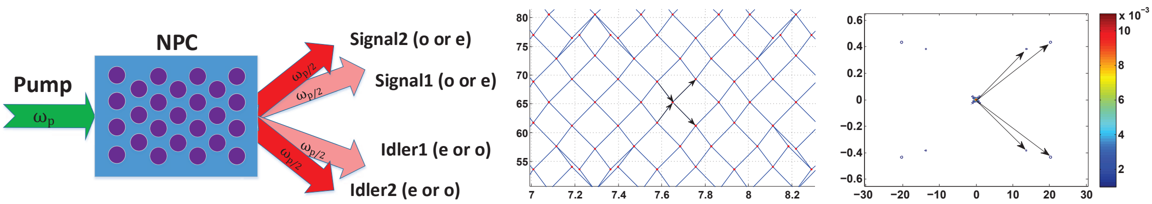
Inspired by the notion of hyperentanglement [1], which refers to the entanglement at multiple degrees of freedom (DOFs) such as polarization, frequency, energy time, *etc*, we focus on producing hyperentanglement at the polarization and spatial mode by using a single designed quasi-periodic NPC to phase match several SPDCs. This method enables to create multiple spatial modes (larger than two) in the path-polarization hyperentanglement in a single quasi-periodic NPC instead of using different cascaded periodic NPCs as in some generation schemes of path entanglement. So this method can be seen as a more compact scheme.



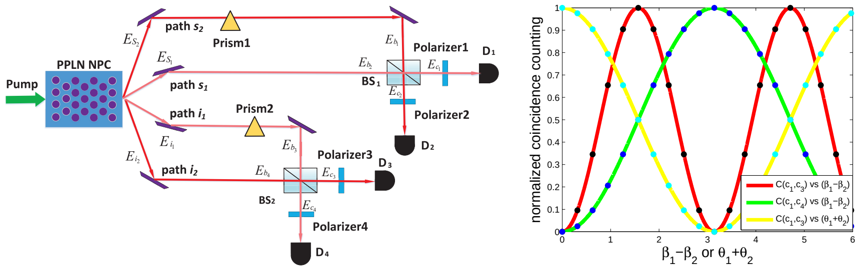
(a) (b) (c)

Fig. 1. (a) Schematic for the generation of path-polarization hyperentangled photon pairs. (b) Structure of the PPLN NPC. Scale is in μm, drawn with an aspect ratio of approximately 1:25. (c) Fourier transform $G(\mathbf{k})$ of the PPLN NPC.

The schematic for the generation of path-polarization hyperentangled photon pairs is displayed in Fig.1(a). We have a pump photon with the wavelength of 532nm injected into the designed NPC, and the signal and idler photons with wavelength of 1064nm are assumed to be generated in our engineering. From an intuitive perspective, the signal and idler photons are firstly polarization entangled; and since they come out from either of the two spatial modes shown in Fig.1(a), they are also path entangled. The NPC displayed in Fig.1(a) is designed to simultaneously accomplish QPM of the 4 different SPDC processes, which can be depicted as $\Delta\mathbf{k}_{jo(e)} = \mathbf{k}_{po} - \mathbf{k}_{s_j o(e)} - \mathbf{k}_{i_j e(o)}$. $\mathbf{k}_{po}$ represents the wave vector of the pump light (o light); $\mathbf{k}_{s(i)_j o(e)}$ represents the wave vectors of signal(idler) light (o light or e light, $j = 1$ or 2). The directions of the wave vectors of beams $\mathbf{k}_{po}$, $\mathbf{k}_{s_1 o(e)}$, $\mathbf{k}_{i_1 e(o)}$, $\mathbf{k}_{s_2 o(e)}$, $\mathbf{k}_{i_2 e(o)}$ are $0°, 58°, -58°, 74°, -74°$ respectively. Periodically poled lithium niobat (PPLN) is chosen as the NPC material and the working temperature is 21°C. Through engineering of the PPLN NPC [3, 4] to accomplish QPM of the mismatch vectors, the structure of PPLN NPC is depicted by Fig.1(b) and the tiling vectors shown in Fig.1(b) are $\mathbf{a}^{(1)} = (7.87, -46.67)\mu m$, $\mathbf{a}^{(2)} = (7.87, 46.67)\mu m$, $\mathbf{a}^{(3)} = (17.33, -55.03)\mu m$, $\mathbf{a}^{(4)} = (17.33, 55.03)\mu m$.

Each red dot with radius of $1\mu m$ in Fig.1(b) is called motif [4] where $\chi^{(2)} = 1$, and $\chi^{(2)} = 0$ in other areas of the PPLN NPC. Fig.1(c) depicts the Fourier transform of the PPLN NPC. We can clearly distinguish Bragg peaks at the positions of the required mismatch vectors $\Delta\mathbf{k}_{1e}, \Delta\mathbf{k}_{1o}, \Delta\mathbf{k}_{2e}, \Delta\mathbf{k}_{2o}$. Based on this crystal, we have quantum state $|\psi\rangle$ of photon pairs as $|\psi\rangle = (C_{eo}^1 |HV\rangle + C_{oe}^1 |VH\rangle)|1\rangle_{s_1}|1\rangle_{i_1}|0\rangle_{s_2}|0\rangle_{i_2} + (C_{eo}^2 |HV\rangle + C_{oe}^2 |VH\rangle)|0\rangle_{s_1}|0\rangle_{i_1}|1\rangle_{s_2}|1\rangle_{i_2}$, where $C_{eo}^1 = C_{oe}^1 = 0.483, C_{eo}^2 = C_{oe}^2 = 0.516$. This is aptly the required path-polarization hyperentanglement.

We design an experimental scheme and the criterions [5] to verify the path and polariztion entanglement separately. The experiment setup is shown in Fig.2(a).



(a) (b)

Fig. 2. (a) Experimental setup which is used to verify path and polarization entanglement. BS_1 and BS_2 are beam splitters with transmission coefficient $T = 0.5$. To verify path and polarization entanglement, we collect coincidence from detectors while adjusting prisms and polarizers. (b) Normalized coincidence counting of D_1, D_3 and D_1, D_4 with respect to phase modulation $(\beta_1 - \beta_2)$ and modulation of polarizer $(\theta_1 + \theta_2)$.

To verify the path entanglement, the polarizers are temporarily removed so that all polarization components are included. With the coincidence of detectors measured, the expected coincidence count rate can be written as $C(c_i, c_j) \propto 1.02 \pm \cos(\beta_1 - \beta_2)$, where the sign $(+)$ holds for (c_1, c_3) and (c_2, c_4), and the sign $(-)$ has to be taken for (c_1, c_4) and (c_2, c_3). Two photon coincidence can be measured by using the phase setting $\beta_1 = 0$, $\beta_1{}^* = \frac{\pi}{2}$ and $\beta_2 = \frac{\pi}{4}, \beta_2{}^* = \frac{3\pi}{4}$. The expected value, $S_k = 2.357 > 2$, verifies the path entanglement between s_1, i_1 and s_2, i_2. Then we discuss the measurement of polarization entanglement [7]. With the rotation of polarizer, we have $C(c_1, c_3) \propto \sin^2(\theta_1 + \theta_2)$. Fig.2(b) depicts the relation between normalized coincidence counting and angular settings of polarizers and shows the visibility, $V = 1$. Two photon coincidence can be measured by using the angular setting $\theta_1 = 0$, $\theta_1{}^* = \frac{\pi}{4}$ and $\theta_2 = \frac{\pi}{8}, \theta_2{}^* = \frac{5\pi}{8}$. The expected value, $S_k = 2.828 > 2$, verifies the polarization entanglement between signal and idler.

Thus, we design a compact generation scheme of path-polarization hyperentangled photon pairs by using QPM of 4 SPDC processes in a designed quasi-period PPLN NPC and a experimental scheme which examine polarization and path entanglement separately, and theoretically get numerical results which verify some predictions about the hyperentanglement.

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