Integrated source of path-polarization hyperentanglement using quasi-periodic nonlinear photonic crystal

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Abstract: A compact scheme for integrated path-polarization entangled photon pairs is proposed by using quasi-periodic nonlinear photonic crystal. We design an experimental scheme and theoretically get numerical results that verify predictions.

Summary: Entanglement plays a key role in the applications of quantum information science such as quantum cryptography, quantum teleportation and dense coding [1]. Consequently, to create and manipulate entanglement using an integrated quantum light source has been a defining experimental goal in recent years.

In our work, we firstly describes the generation of path-polarization hyperentangled photon pairs by using Quansi-Phase-Matching (QPM) method of 4 SPDC processes in a designed quasi-period nonlinear photonic crystal (NPC) [2]. A pump photon with the frequency of ω_p injected into the designed NPC—in which it will get through either of the 4 SPDC processes. The signal and idler photons with frequency $\omega_p/2$ 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. Assuming the wavelength of the pump light is 532nm and that of the signal and idler light is 1064nm, we calculate out the mismatch vector G_{1e} ,G_{1o} ,G_{2e} and G_{2o}.

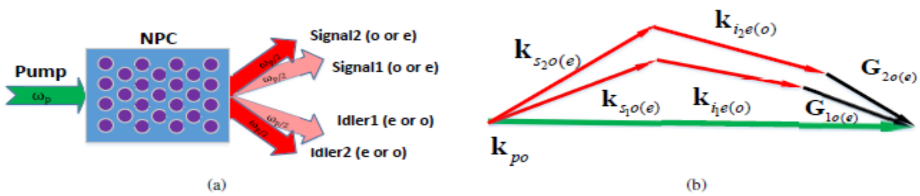

FIG. 1: (a) Schematic for the generation of path-polarization hyperentangled photon pairs. (b) QPM condition for the 4 SPDC processes in generation of path-polarization hyperentangled photon pairs.

We choose periodically poled lithium niobat (PPLN) as the material of NPC and the working temperature is 21℃. Fig.2 depicts the Fourier transform of the PPLN NPC—in which Bragg peaks at the positions of the required mismatch vectors G1e,G1o,G2e,G2o are distinguished.

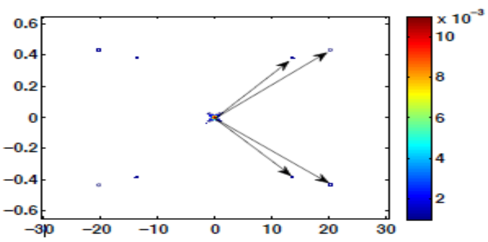

FIG. 2: Fourier transform g(k) of the PPLN NPC. Scale is inμm−1.The arrows indicate the mismatch vectors G2o,G1o,G1e,G2e respectively in clockwise.

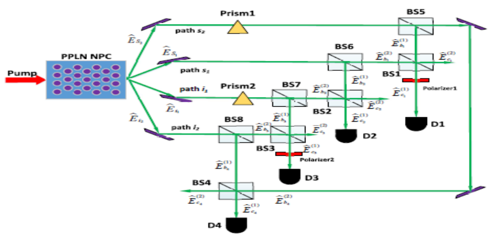

FIG. 3: Structure of the experimental setup.

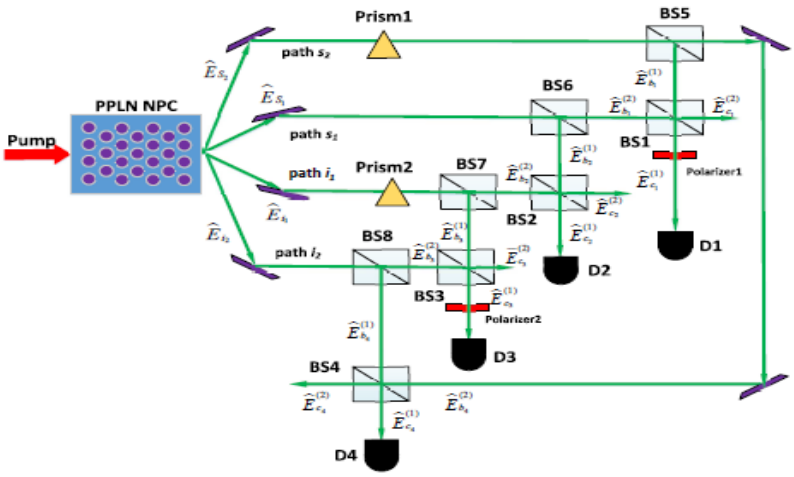

FIG. 3: Structure of the experimental setup.

Under the first-order perturbation approximation [3], through the QPM of 4 SPDC processes in the designed PPLN NPC, we acquire the two-photon state and simplified it as follows:

$$\left|\varphi\right\rangle = (C_{eo}^{1}\left|HV\right\rangle + C_{oe}^{1}\left|VH\right\rangle)\left|1\right\rangle_{S1}\left|1\right\rangle_{i1}\left|0\right\rangle_{S2}\left|0\right\rangle_{i2} + (C_{eo}^{2}\left|HV\right\rangle + C_{oe}^{2}\left|VH\right\rangle)\left|0\right\rangle_{S1}\left|0\right\rangle_{i1}\left|1\right\rangle_{S2}\left|1\right\rangle_{i2}$$

We further design an experimental scheme and the criterions to verify the path and polarization entanglement simultaneously. The experiment setup is shown in Fig.3 and it incorporates the Hong-Ou-Mandel-type quantum inference measurements [4, 5]. Prism1 and Prism2 are used to modify the phase of signal and idler photons in path s2 and i1, which gives us sufficient control over the phase difference between photons to implement interference. For BS1, BS2, BS3, BS4, the transmission coefficient T = 0.5. Since interferences in BS2 and BS4 are temporarily not needed in our verification processes of the hyperentanglement, we have T = 0 for BS5, BS7, and T = 1 for BS6, BS8—which means light fields will not get into the input-ports of BS2 and BS4. Polarizer1 and Polarizer2 are used to pick certain polarization components. Besides, our works justify the methods to measure the path entanglement and the final numerical results which verify our predictions about the hyperentanglement from both path entanglement and polarization entanglement. The details of the results are depicted in Fig.4.

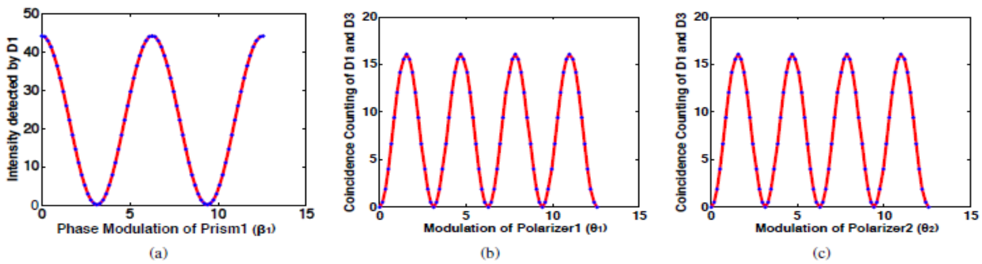

FIG. 4: (a) The intensity detected by D1 with respect to phase modulation of Prism1 (b1). (b) Coincidence Counting of D1 and D3 with respect to modulation of Polarizer1 (q1). (c) Coincidence Counting of D1 and D3 with respect to modulation of Polarizer2 (q2).

Finally, we discuss how the basic model can be expanded for the generation of multi-partite and two-photon path-polarization hyperentanglement and show an 8 SPDC situation as an example.

Conclusions In this work, 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. The design parameters of the PPLN NPC including the working temperature are all given and its structure is obtained. Also, Fourier transform of the PPLN NPC structure is given—in which the distinguished Bragg peaks at the required mismatch vectors demonstrate the efficiency of 4 SPDC processes. Moreover, we design an experimental scheme which incorporates Hong-Ou-Mandel-type quantum inference measurements to examine path and polarization entanglement simultaneously, and theoretically get numerical results which verify the predictions about the hyperentanglement. Finally, this method can also be expanded for generation of multi-partite and two-photon path-polarization hyperentanglement.

References

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