Frequency-Multipath Hyperentangled Photons Generation Using Quasi-Phase-Matched Nonlinear Photonic Crystal

Chaoxiang Xi[1], Yizhou Ding[1], Bo ji[1], Xinbao gong[2] and Guangqiang He[1,*]
[1]State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[2]Institute of Media, information, and Network, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
**Corresponding author: gqhe@sjtu.edu.cn*

Abstract: A quasi-phase-matched two-dimensional (2D) nonlinear photonic crystal (NPC) whose poling direction is perpendicular to the pump beam, is shown to generate frequency-multipath hyperentanglement where six paths are included.

1. Introduction

Compared with the ordinary quantum entanglement source, the hyperentanglement source is more versatile. Hyperentangled photons can realize various kinds of quantum operations such as Bell-state analysis [1], quantum dense coding and advanced quantum computation [2].

At the same time, it is admitted that NPC plays a mainly role in producing various quantum entanglement [3,4]. In this work, we introduce a compact scheme to produce frequency-multipath hyperentanglement using only one well-designed 2D NPC.

2. Frequency-Multipath Hyperentangled Photon Source Scheme

A frequency-multipath hyperentanglement source scheme based on a 2D NPC is designed as shown in Fig.1. The core device of the scheme is a type-I (e⟶o+o) phase-matched 5% MgO-doped $LiNbO_3$ crystal working in room temperature (25℃), whose second order susceptibility $\chi^{(2)}$ is modulated in x and y dimensions in an ordered fashion.

The pump beam is incident on the surface of the NPC along the z-axis. The pump plane is constructed by the pump wave vector $\vec{k}_p$ and the unit vector parallel to the y-axis, where $\vec{k}_p$ is perpendicular to the xOy plane. Signal and idler are located above and below the pump plane, respectively. There are three couples (Path1&4, Path2&5 and Path3&6) of optional paths for each newly-generated spontaneous parametric down-conversion (SPDC) photon pair in total. Besides, all the six paths are designed to be evenly distributed around the vector $\vec{k}_p$. Therefore, we set $\theta_j = (\mathrm{j}-1) * \pi/3$ (where j=1, 2, 3) as shown in Fig.1, and the angle named φ between $\vec{k}_s$ and $\vec{k}_p$ is equal to the one between $\vec{k}_i$ and $\vec{k}_p$. Respectively, $\vec{k}_s$ and $\vec{k}_i$ are wave vector of signal and idler.

The frequency-multipath hyperentanglement can be expressed as the tensor product of two entangled states:

$$|\psi\rangle = \frac{1}{\sqrt{3}}\left(\left|(\theta_1)_S,(\theta_1+\pi)_I\right\rangle + \left|(\theta_2)_S,(\theta_2+\pi)_I\right\rangle + \left|(\theta_3)_S,(\theta_3+\pi)_I\right\rangle\right) \otimes \frac{1}{\sqrt{2}}\left(\left|\omega_{1,S},\omega_{2,I}\right\rangle + \left|\omega_{2,S},\omega_{1,I}\right\rangle\right). \quad (1)$$

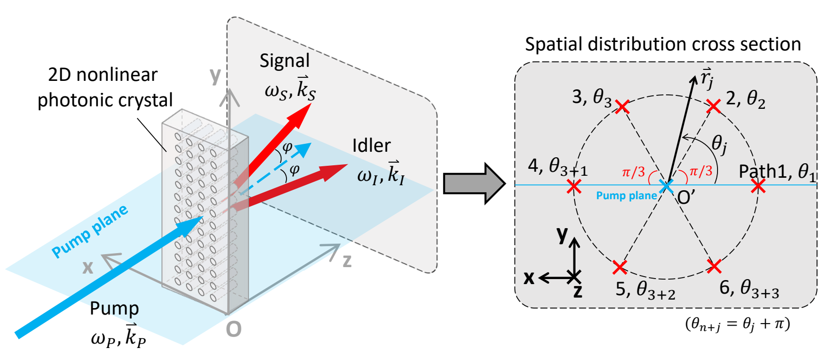

Fig. 1. Frequency-multipath hyperentangled photon source scheme.

Here, the subscript S and I represent signal and idler respectively. According to the spatial distribution cross section in Fig.1, $(\theta_j)_l$ (where *l*=S, I) means that the angle between radial vector $\vec{r}_p$ and the pump plane equals θ_j, $\omega_{m,l}$ (where *m*=1, 2; *l*=S, I) means that the angular frequency of *l* equals ω_m.

3. Design Details of the Nonlinear Photonic Crystal

Fig.2 shows the Quasi-phase-matching (QPM) conditions (A and B) that each of the three couples of SPDC processes needs to satisfy. In other words, the NPC needs to compensate six SPDC processes at the same time.

The wavelength of pump is set at $\lambda_p = 775\text{nm}$, and we choose $\lambda_S = 1530\text{nm}$, $\lambda_I = 1570.5\text{nm}$. Additionally, we ensure that the mismatch along the z-axis is zero. Correspondingly, $\varphi = 0.1862\text{rad}$, $|\Delta\vec{k}_j| = 4.4346 \times 10^{-2}\mu\text{m}^{-1}$ (where j=1, 2, 3).

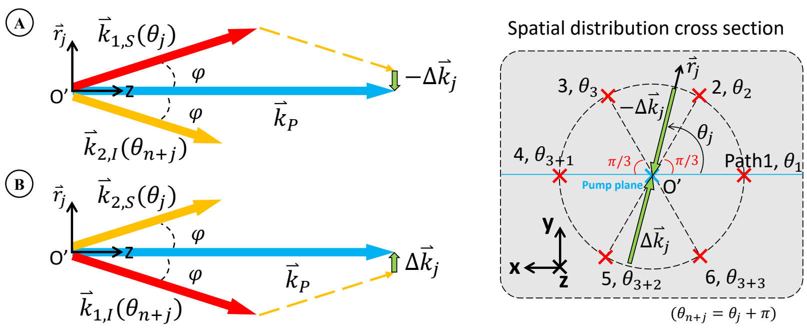

Fig. 2. QPM conditions for frequency-multipath hyperentanglement generation

The NPC displayed in Fig.3(a) is the design result. In Fig.3(a), the subfigure surrounded by dotted lines is a partial enlarged view of the NPC, where each blue circle with radius of 56.67μm is called a motif [5]. In the motif $\chi^{(2)} = +1$, while $\chi^{(2)} = -1$ in the rest area of the NPC. And the NPC's Fourier transform is shown in Fig.3(b).

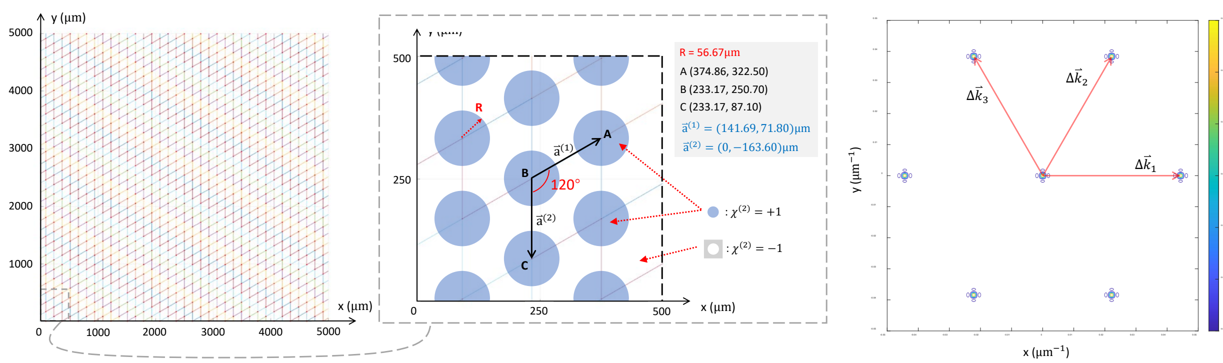

Fig. 3. (a) Structure of the NPC. (b) Fourier transform of the NPC.

4. References

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