On-Chip Generation of Hyperentanglement Using a Single Nanophotonic Waveguide

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Abstract: We generated a two-mode hyperentangled state using a nanophotonic lithium niobate waveguide, achieving high-quality polarization, energy-time, and quadrature amplitude-phase entanglement. Our scheme could stand as an efficient approach to facilitate high-capacity quantum communication.

1. Introduction

Hyperentanglement builds upon the concept of traditional entanglement by entangling particles in multiple degrees of freedom (DOFs) simultaneously [1]. Previous efforts in hyperentanglement generation have predominantly focused on harnessing hyperentanglement encoded in two DOFs [2–4], while the research on hyperentanglement in three DOFs is scarce. Moreover, precise control over multiple DOFs requires advanced optical systems and synchronization [5], making the experimental realization and stabilization of these states a daunting task.

In order to overcome the technical complexity for hyperentanglement preparation, we propose a hyperentangled state generation scheme based on one nanophotonic periodically poled lithium niobate (PPLN) waveguide. including polarization, energy-time, and quadrature amplitude-phase (X-P) DOFs. By using a single waveguide that is periodically poled to address quasi-phase-matching conditions for three DOFs, our scheme significantly reduces the physical and operational complexity commonly associated with hyperentanglement setups, eliminating the need for multiple disparate components to control each DOF separately.

2. Hyperentangled Two-mode Source Scheme

In our scheme, we utilize one nanophotonic PPLN waveguide to implement hyperentanglement across three DOFs, as shown in Fig. 1(a), with its cross section depicted in Fig. 1(b). Fabricated using a $0.6\,\mu$m thick z-cut lithium niobate crystal film, the waveguide leverages the material's excellent electro-optic properties, high nonlinear coefficients, and wide transparency range. A trapezoidal center section of the waveguide, measuring 8 mm in length, efficiently transmits pump, signal, and idler light, optimizing phase matching conditions necessary for effective frequency conversion processes. Detailed simulations provide effective refractive index dispersion curves for both ordinary light (o-light) and extraordinary light (e-light) illustrated in Fig. 1(c).

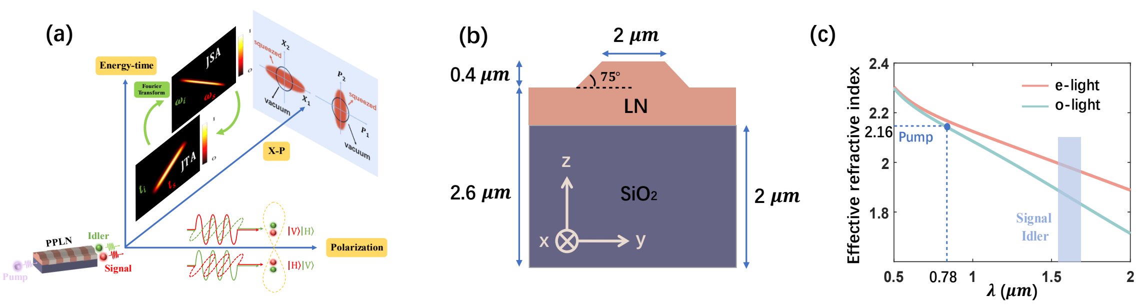

Fig. 1. (a) The schematic diagram of generating photon pairs entangled simultaneously in three degrees of freedom, including polarization, energy-time, and quadrature amplitude-phase. (b) The cross section of our PPLN waveguide, with its dispersion curve for both e-light and o-light shown in (c).

3. Quantum Characteristics

Fig. 2(a)∼(d) show conversion efficiencies corresponding to type-II and type-I phase matching conditions. We can see that process $o \to o + e$ and $o \to e + o$ have nearly identical conversion efficiency functions. The joint spectral amplitude $A(\omega_s, \omega_i)$ and its Schmidt decomposition result are shown in Fig. 2(e) and Fig. 2(f), respectively, with corresponding joint uncertainty product $\Delta_{un} = 0.4113 < 1$. The generated two-mode state $|\psi\rangle$ can be expressed as a superposition of photon number states $|k,k\rangle$, that is, $|\psi\rangle = \sum_k C_{k,k}|k,k\rangle$. The first 10 coefficients $C_{k,k}$ are shown in Fig. 2(g). We also plot the iterative process of the von Neumann entropy $S_r(k)$ with k in Fig. 2(h),which finally converges to 0.192, indicating the generated state has entanglement in X-P DOF.

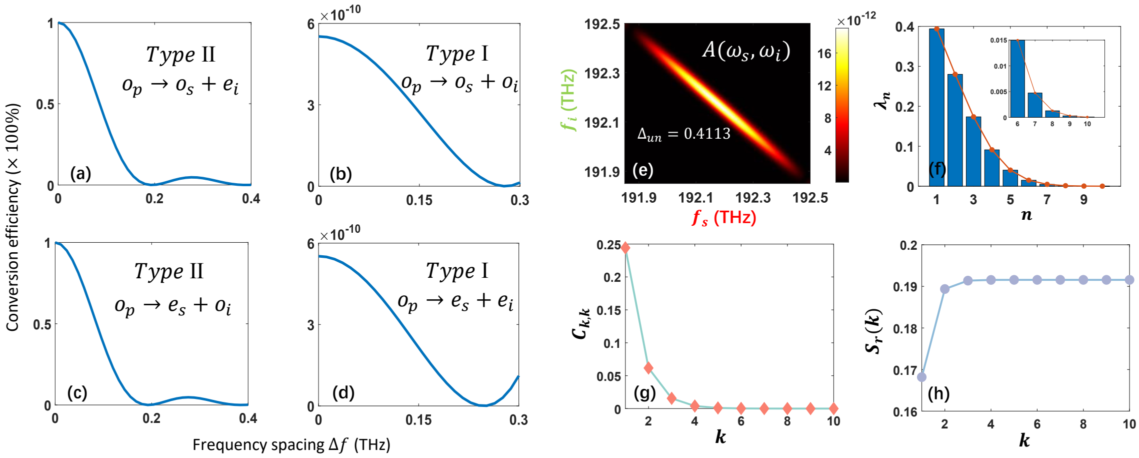

Fig. 2. (a)∼(d) Conversion efficiencies for four possible quantum process in the PPLN waveguide. (e) The JSA of the generated two-mode state with its first 10 Schmidt decomposition coefficients shown in (f). (g) The first 10 coefficients $C_{k,k}$ of the photon number state $|k,k\rangle$. (h) The squeezing degree S_r of the generated two-mode squeezed state, which finally reaches 0.192.

4. Conclusion

We propose a compact scheme to generate hyperentanglement state in polarization, energy-time and X-P DOFs in the nanophotonic PPLN waveguide. The two type-II quantum process in the waveguide can exist simultaneously and occur approximately with equal probability, resulting in maximally entangled Bell state in polarization DOF. Moreover, the joint uncertainty product $\Delta_{un} = 0.4113 < 1$ while the von Neumann entropy S_r of the generated two-mode squeezed state can reach 0.192. We believe that our proposed scheme for preparing hyperentangled states is generally applicable. The key principle is to control dispersion by designing crystal structures to achieve quasi-phase matching for manipulating multiple DOFs. Our approach could pave the way for high-capacity and high-speed quantum communication in the future.

The authors acknowledge the support from the National Natural Science Foundation of China (Grant No. 62075129) and the Open Project Program of the SJTU-Pinghu Institute of Intelligent Optoelectronics (No. 2022SPIOE204).

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