Coherent manipulation of a three-dimensional maximally entangled state

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Abstract: Maximally entangled photon pairs with a spatial degree of freedom is a potential way for realizing high capacity quantum computing and communication. However, methods to generate such entangled states with high quality, high brightness, and good controllability are needed. Here, a scheme is experimentally demonstrated that generates spatially maximally entangled photon pairs with an orbital angular momentum degree of freedom via spontaneous parametric down-conversion in a nonlinear crystal. Compared with existing methods using postselection, the technique can directly modulate the spatial spectrum of down-converted photon pairs by engineering the input pump beam. In addition, the relative phase between spatially entangled photon pairs can be easily manipulated by preparing the relative phase of input pump states.

1. Introduction

Engineering the entangled state is an important direction in quantum technology and forms a basis for quantum information processing. In particular, both the realization of a high-dimensional, maximally entangled state (MES) and its coherent manipulation are indispensable for investigating quantum physics and information, i.e., high-dimensional (HD) quantum computation. HD-MES encoded in orbital angular momentum (OAM) via spontaneous parameter down-conversion has been a well-known and effective method and much progress has been made. Specially, a three-dimensional MES was prepared in Ref. [1] and a higher dimensional MES to d=12 was studied in Ref. [2]. However, most of OAM-based MES are generated via post-selection of the quantum state $\sum_{l=-\infty}^{\infty} c_l \left|l\right\rangle_A \left|-l\right\rangle_B$ by using a Gaussian pump, which is not indeed a maximally entangled state. Here, we first realize a two-photon, three-dimensional, OAM-based MES without post-selection via the SPDC process, and experimentally demonstrate the ability of amplitude- and phase- modulation in our system. The approach was to engineer the pump beam with an arbitrary superposition of Laguerre-Gauss (LG) modes. The state of down-converted photon pairs could then be manipulated independently based on OAM conservations in SPDC. To check the non-classical characteristics of the prepared three-dimensional MES, we performed the Bell-type inequality (S=2.3729±0.0159) and high-dimensional quantum state tomography (F=0.8581±0.0028). Also, the spatial spectrum of the down-converted photons was calculated. Comparing with the existing schemes, there were some advantages of these protocols. i) It did not require post selections and ii) the arbitrary phase between different superposition terms could be easily engineered by preparing the input beams', which is benefitcial to generate the high-dimensional Bell state.

2. Principle

The down converted photon pairs have the form $\sum_{l=-\infty}^{\infty} c_L \left|l\right\rangle_A \left|L-l\right\rangle_B$ for single pure state pump $\left|L\right\rangle_P$; by analogy, it can be written as $\sum_L \sum_{l=-\infty}^{\infty} c_l^{'} \left|l\right\rangle_A \left|L-l\right\rangle_B$ when the pump is a superposition of $\sum_L C_L \left|L\right\rangle_P$. Engineering a suitable pump state of $C_{-2}\left|-2\right\rangle + C_0\left|0\right\rangle + C_2\left|2\right\rangle$, the down-converted entangled state can be generated as a three-dimensional MES $1/\sqrt{3}\left(\left|-1-1\right\rangle + e^{i\theta_0}\left|00\right\rangle + e^{i\theta_2}\left|11\right\rangle\right)$, where the amplitude and phase between different modes can be modulated classically. The optical setup, and main results of the Bell-CGLMP inequality and high-dimensional quantum state tomography can be found in our recently original article [3].

3. References

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