Preparation and purification of four-photon Greenberger–Horne–Zeilinger state

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Abstract

We present an efficient scheme for the preparing and purifying of the four-photon Greenberger–Horne–Zeilinger (GHZ) state based on linear optics and postselection. First, we describe how to create a four-photon GHZ state in both polarization and spatial degrees of freedom from two pairs. Moreover, in the presence of depolarization noise our scheme is capable of purifying the desired state. In the regime of weak nonlinearity we design an indirect photon number-resolving detection to distinguish two states of the two pairs. At last, a fourfold coincidence detector click indicates the creation of a polarization-entangled four-photon GHZ state.

Keywords: preparation and purification, four-photon Greenberger–Horne–Zeilinger state, cross-Kerr nonlinearity

(Some figures may appear in colour only in the online journal)

1. Introduction

Multipartite entanglement [1, 2] is one of the most fundamental and intriguing features of quantum mechanics and a resource for a variety of quantum information processing tasks [3–8]. Currently, optical quantum systems [9, 10] are prominent candidates for quantum information processing. Based on the inherent nature of photons, a photon represents a qubit and photons can be made to interact with each other using cross-Kerr nonlinearities [11, 12]. Remarkably, in 2001, Knill et al [13] have shown a scalable quantum computation, in principle, with linear optics, single-photon sources and detectors. Motivated by this report, a series of researches for optical quantum information processing have been done in succession [14–17].

There are several methods to prepare multi-photon entangled states based on linear optics and cross-Kerr nonlinearities. As a standard method, experimentally, a parametric down-conversion (PDC) source can emit one pair of polarization-entangled photons with a given probability [18]. Then, one can transform two pairs of polarization entangled photons into the three-photon Greenberger–Horne–Zeilinger (GHZ) state [19], four-photon GHZ state [20], hyper-entangled state [21, 22], and so on. On the other hand, in the regime of weak cross-Kerr nonlinearities, one can construct quantum nondemolition detection (QND) [23–29] to project signal photons onto a desired subspace. In general, the signal modes may be fed by several single photons or some entangled photons. For example, Nemoto and Munro [25] proposed a two polarization qubit entangling gate, and Barrett et al [26] described a method of nondestructive Bell-state detection, where the detections of coherent probe beams in two schemes are all homodyne measurement of the position quadrature.

In this paper, we focus on the preparation and purification of the four-photon GHZ state. Especially, we describe a method to purify the desired four-photon state in the depolarization-noise channel.

2. Creation of four-photon eight-qubit GHZ state

As is well known, when a short pulse of ultraviolet light passes through the β-barium-borate (BBO) crystal, a pair of
polarization entangled photons may be prepared in spatial modes $a_1$ and $b_1$, as shown in figure 1. Also, another pair may be emitted in spatial modes $a_2$ and $b_2$ because of the function of a mirror. We suppose that two independent photon pairs are created in state

$$\sum_{i,j=1}^{2} \left( |H\rangle_{a_i} |V\rangle_{b_i} - |V\rangle_{a_i} |H\rangle_{b_i} \right) \times \left( |H\rangle_{a_j} |V\rangle_{b_j} - |V\rangle_{a_j} |H\rangle_{b_j} \right).$$

(1)

where $a_{ij}$ and $b_{ij}$ ($i, j = 1, 2$), respectively, represent four spatial modes, $|H\rangle$ ($|V\rangle$) indicates the state of a horizontally (vertically) polarized photon. Obviously, the quantum state is combined by two parts, that is, the $i=j$ part and $i \neq j$ part, we also called two cases, that is, $i=j$ and $i \neq j$. For $i=j$, the two pairs are either both created in the spatial modes $a_1$ and $b_1$, or they are created in the modes $a_2$ and $b_2$. While, for $i \neq j$, it means that there is one photon in each spatial modes $a_1, b_1, a_2$ and $b_2$, respectively.

In figure 1, each polarizing beam splitter (PBS) is used to transmit $|H\rangle$ polarization photons and reflect $|V\rangle$ polarization photons. The beam splitters (BSs) represent 50:50 polarization-independent BSs. The half wave plate $R_{90}$ is used to convert the polarization state $|H\rangle$ into $|V\rangle$ or vice versa. $C_1$, $C_2$, $D_1$, $d_1$, $E_i$, and $e_i$ ($i = 1, 2, 3, 4$) are the different spatial modes, respectively. Through the setup towards the spatial modes $D_i$ and $d_i$ the involved components of equation (1) evolve as

$$|H\rangle_{a_1} \rightarrow \frac{1}{\sqrt{2}} \left( |H\rangle_{D_1} + |H\rangle_{D_2} \right),$$

$$|H\rangle_{a_2} \rightarrow \frac{1}{\sqrt{2}} \left( |H\rangle_{d_1} + |H\rangle_{d_2} \right),$$

(2)

$$|V\rangle_{a_1} \rightarrow \frac{1}{\sqrt{2}} \left( |V\rangle_{D_1} + |V\rangle_{D_2} \right),$$

$$|V\rangle_{a_2} \rightarrow \frac{1}{\sqrt{2}} \left( |V\rangle_{d_1} + |V\rangle_{d_2} \right),$$

(3)

$$|H\rangle_{b_1} \rightarrow \frac{1}{\sqrt{2}} \left( |H\rangle_{D_1} + |H\rangle_{D_2} \right),$$

$$|H\rangle_{b_2} \rightarrow \frac{1}{\sqrt{2}} \left( |H\rangle_{d_1} + |H\rangle_{d_2} \right),$$

(4)

$$|V\rangle_{b_1} \rightarrow \frac{1}{\sqrt{2}} \left( |V\rangle_{D_1} + |V\rangle_{D_2} \right),$$

$$|V\rangle_{b_2} \rightarrow \frac{1}{\sqrt{2}} \left( |V\rangle_{d_1} + |V\rangle_{d_2} \right).$$

(5)

Consider now the case that the four photons are emitted, one in each spatial mode $D_1$ (or $d_1$), $D_2$ (or $d_2$), $D_3$ (or $d_3$), and $D_4$ (or $d_4$). Specifically, for $i = j$, after the equipment the satisfactory state reads

$$\phi_0 = \frac{1}{2} \left( |H\rangle_{D_1} |V\rangle_{D_2} |V\rangle_{D_3} |H\rangle_{D_4} + |H\rangle_{D_1} |V\rangle_{d_2} |V\rangle_{d_3} |H\rangle_{d_4} \right) + \frac{1}{2} \left( |V\rangle_{D_1} |H\rangle_{D_2} |H\rangle_{D_3} |V\rangle_{D_4} + |V\rangle_{D_1} |H\rangle_{d_2} |H\rangle_{d_3} |V\rangle_{d_4} \right)$$

$$\equiv \frac{1}{2} \left( |HVHV\rangle_{D_1D_2D_3D_4} + |HHVV\rangle_{d_1d_2d_3d_4} \right)$$

(6)
While for $i \neq j$, the state evolves as [21, 22]

$$\psi_0 = \frac{1}{2} \left( |H\rangle_d |d\rangle_s + |V\rangle_d |d\rangle_s + |H\rangle_d |d\rangle_s - |V\rangle_d |d\rangle_s \right) + \frac{1}{2} \left( |H\rangle_d |d\rangle_s + |V\rangle_d |d\rangle_s + |H\rangle_d |d\rangle_s + |V\rangle_d |d\rangle_s \right).$$

Then, after four half wave plates and PBSs, one obtains the desired four-photon entangled state containing entanglement in both polarization and spatial degrees of freedom. That is, for $i = j$, the state

$$\psi = \frac{1}{2} \left( |HVVH\rangle + |VHHV\rangle \right)_{i=1,2,3,4} \times (e_{iE} e_{iE} + e_{iE} e_{iE}).$$

So far, we describe an efficient scheme to create four-photon eight-qubit GHZ states which are entangled in polarization and spatial modes. We derive two representations, which contain all possible cases about emitted four photons, namely, $i = j$ and $i \neq j$.

### 3. Polarization entanglement purification using spatial entanglement

In practice, we note that the prepared entangled photons may suffer from channel noise when traveling from a source to a destination (generally say, Alice, Bob, Charlie and David for quantum information processing). Notice that each pair of spatial modes $d_i$ and $D_i$ $(i = 1, 2, 3, 4)$ is the connection between the central source and the common observing location, so, for a given $i$, we here suppose that the spatial modes $d_i$ and $D_i$ suffer the same depolarization consisting of both bit-flip and phase errors. Furthermore, because an impact of noise on spatial modes can be easily avoided [14], we assume that only the polarization entanglement suffer from channel noise [15, 22]. The following task of our scheme is to purify the polarization entanglement by using spatial entanglement based on linear optics and multi-fold coincidence detections.

In a depolarization channel, the created entangled states $|\phi_0\rangle$ and $|\psi_0\rangle$ may suffer from bit-flip and phase-flip errors. Now, let us take the state $|\psi_0\rangle$ for example. We here suppose that two spatial modes $d_1$ and $D_1$ are faultless and only the photons in spatial modes $d_i$ and $D_i$ $(i = 2, 3, 4)$ suffer depolarization. It implies that Alice, whose location associates with spatial modes $e_1$ and $E_1$, prepares pairs and distributes them to other locations. Clearly, the initial state may be transformed to one of the following sixteen four-photon entangled states:

$$\psi^+_i = \frac{1}{2} \left( |HVHV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right) \pm |VHHV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right);$$

$$\psi^-_2 = \frac{1}{2} \left( |HVHV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right) \pm |VHHV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right);$$

$$\psi^-_3 = \frac{1}{2} \left( |HHHV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right) \pm |VHVV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right);$$

$$\psi^-_4 = \frac{1}{2} \left( |HHHV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right) \pm |VHVV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right);$$

$$\psi^-_5 = \frac{1}{2} \left( |HHHH\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right) \pm |VVVV\rangle |d_1d_2d_3d_4 + |d_1d_2d_3d_4 \right);$$

After the action of the four half wave plates and PBSs, as shown in figure 1, the combined system then evolves as

$$\psi^{+}_i \xrightarrow{\text{channel}} \frac{1}{2} \left( |HHVV\rangle + |VVHH\rangle \right)_{E_1E_2E_3E_4} \pm \left( |HVHV\rangle + |VHHV\rangle \right)_{E_1E_2E_3E_4},$$

$$\psi^{-}_2 \xrightarrow{\text{channel}} \frac{1}{2} \left( |HHHH\rangle + |VVVV\rangle \right)_{E_1E_2E_3E_4} \pm \left( |HHV\rangle + |VHHV\rangle \right)_{E_1E_2E_3E_4},$$

$$\psi^{-}_3 \xrightarrow{\text{channel}} \frac{1}{2} \left( |HHHV\rangle + |VHHV\rangle \right)_{E_1E_2E_3E_4} \pm \left( |HHH\rangle + |VVVV\rangle \right)_{E_1E_2E_3E_4},$$

$$\psi^{-}_4 \xrightarrow{\text{channel}} \frac{1}{2} \left( |HHHV\rangle + |VHHV\rangle \right)_{E_1E_2E_3E_4} \pm \left( |HHH\rangle + |VVVV\rangle \right)_{E_1E_2E_3E_4}.$$
$$\left| \psi^\pm \right\rangle = \frac{1}{\sqrt{2}} \left( \left| HHHV \right\rangle + \left| VVHV \right\rangle \right)_{e_1e_2e_3e_4}$$

$$\pm \left( \left| HVVV \right\rangle + \left| VHHH \right\rangle \right)_{e_1e_2e_3e_4} \tag{22}$$

$$\left| \omega^\pm \right\rangle = \frac{1}{\sqrt{2}} \left( \left| HVVV \right\rangle + \left| VHHH \right\rangle \right)_{e_1e_2e_3e_4}$$

$$\pm \left( \left| HHHV \right\rangle + \left| VVHV \right\rangle \right)_{e_1e_2e_3e_4} \tag{23}$$

$$\left| \omega^\pm \right\rangle = \frac{1}{\sqrt{2}} \left( \left| HVHV \right\rangle + \left| VVHH \right\rangle \right)_{e_1e_2e_3e_4}$$

$$\pm \left( \left| HHVV \right\rangle + \left| WVHV \right\rangle \right)_{e_1e_2e_3e_4} \tag{24}$$

$$\left| \omega^\pm \right\rangle = \frac{1}{\sqrt{2}} \left( \left| HVVV \right\rangle + \left| VHHH \right\rangle \right)_{e_1e_2e_3e_4}$$

$$\pm \left( \left| HHHV \right\rangle + \left| VVHV \right\rangle \right)_{e_1e_2e_3e_4} \tag{25}$$

So we can conclude that the errors both from phase-flip and bit-flip can be corrected based on fourfold coincidence detection and postselection. More specifically, after evolution of the equipment, if one of the four-fold coincidence detections $e_1$, $e_2$, $E_1$, and $e_4$ (or $E_1$, $E_2$, $e_3$, and $E_4$) clicks, for example, we may conclude that the initial state $\left| \psi^\pm \right\rangle$ suffers both phase-flip and bit-flip on one of the polarization qubits and evolves as $\left| \omega^\pm \right\rangle$. On the other hand, with the fourfold coincidence detector click, the four-photon hyperentangled state collapses into polarization entangled state

$$\frac{1}{\sqrt{2}} \left( \left| HHVV \right\rangle + \left| VHHH \right\rangle \right)$$

or

$$\frac{1}{\sqrt{2}} \left( \left| HHVV \right\rangle + \left| VVHV \right\rangle \right).$$

In all, the phase-flip error can be erased in postselection and the bit-flip can be corrected by the following local bit-flip operation, which can be easily realized by some half wave plates. Furthermore, extending the same procedure allows us to analyze the case $i = j$. It is worth noting that in order to obtain four-photon GHZ states rather than two-GHZ-pair states (entangled state $\frac{1}{2} \left( \left| HHVV \right\rangle + \left| VHHH \right\rangle + \left| HVHV \right\rangle + \left| VVHH \right\rangle \right)$, for example) there is an additional constraint (a set of spatial modes $d_1$ and $D_1$, for example, are faultless) for $i \neq j$, while for $i = j$ there is not the above constraint. At last, without loss of generality, in order to obtain the four-photon polarization-entanglement GHZ state

$$\frac{1}{2} \left( \left| HHHH \right\rangle + \left| VVHH \right\rangle \right),$$

for example, we list the required operations on the four photons corresponding to the results of fourfold coincidence detections, as shown in Table 1.

| FCD | $i = j$ | $i \neq j$ |
|-----|---------|--------|
| $e_1e_2e_3e_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $E_1E_2E_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $e_1e_2E_3e_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $E_1E_2e_3e_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $e_1e_2e_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $E_1E_2e_3e_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $e_1e_2E_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $E_1E_2E_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $e_1E_2E_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $E_1e_2E_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $e_1e_2e_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |
| $E_1E_2e_3E_4$ | $i \otimes i \otimes i \otimes i$ | $i \otimes i \otimes i \otimes i$ |

4. Photon number-resolving detection

As a matter of fact, if we cannot distinguish between $i = j$ and $i \neq j$, two cases of the created four-photon, when fourfold coincidence detector clicks we do not tell exactly what operation is required and what state has been prepared. However, it is noting that the action to distinguish between two cases must not destroy the nature of entangled photons. Thus, it becomes very important to distinguish the two cases in a nondestructive way.

Considering for $i = j$ there are two photons in each spatial mode and $b_1$ (or $a_2$ and $b_2$), while for $i \neq j$ there is one photon in each spatial mode and $b_2$ or not. Now, in the regime of weak nonlinearities ($\theta \approx 10^{-2}$), we design a setup of QND to determine the four photons created by PDC sources whether in the case $i = j$ or in the alternative $i \neq j$. As shown in Figure 2, signal modes $a_1$ and $a_2$ are two spatial modes of the emitted photons, coherent probe beam $|\sqrt{2}|a\rangle$ followed by BSs, two single-qubit phase gates $R(-\theta)s$ and cross-Kerr nonlinearities are used to construct cross-phase modulation, 1, 2, 3, and 4 are four spatial modes of the probe beams. After a series of transformations of the setup, the states of the combined system of the two signal modes and the location, or the distances from the source to the locations $e_i$ and $E_i$ ($i = 2, 3, 4$) are much larger than the distance from the source to the location $e_1$ and $E_1$. Then, note that the evolutions of photons at each PBS are local and each pair of spatial modes $d_i$ and $D_i$ have the same location, that is, spatial modes $d_i$ and $D_i$ (with the same setting) suffer from bit-flip and phase-flip errors in a channel at the same time.
probes beams 

\[ |1, 1\rangle_{a_1a_2} |\alpha\rangle |\sigma\rangle \] (26)

and

\[ \frac{1}{\sqrt{2}} (|0\rangle, 2)_{a_1a_2} + |2, 0\rangle_{a_1a_2}) |\alpha\rangle |\sigma\rangle \] (27)

evolve as

\[ |1, 1\rangle_{a_1a_2} |\sqrt{2} \alpha\rangle |0\rangle_2 \] (28)

and

\[ \frac{1}{\sqrt{2}} [\sqrt{2} \cos \theta] (|0\rangle, 2)_{a_1a_2} |\sqrt{2} \alpha \sin \theta\rangle_2 \]

\[ + |2, 0\rangle_{a_1a_2} |\sqrt{2} \alpha \sin \theta\rangle_2 \], (29)

respectively. Here \( |m, n\rangle_{a_1a_2} \) represents a two-spatial mode state, with \( m \) photons in mode \( a_1 \) and \( n \) photons in mode \( a_2 \). Then we introduce an indirect photon number-resolving detection [28] on spatial mode 2 by using another coherent state \( |\beta\rangle \). Here, the photon number-resolving detection serves two purposes. It is used to distinguish between the states \( |0\rangle_2 \) and \( |2\rangle_{a_1a_2} \) but do not distinguish \( |\sqrt{2} \alpha \sin \theta\rangle_2 \) from \( |\sqrt{2} \alpha \sin \theta\rangle_2 \) and project two signal photons onto a desired subspace, simultaneously. After the evolution of BSs and cross-Kerr medium followed by a projection \( |n\rangle \langle n| \) on spatial mode 4, one can obtain specific value of photon number \( n \) in mode 2, as described by Lin et al in [29]. As a result, the value of projection \( n = 0 \) corresponding to a vacuum state project two signal photons onto the state \( |1, 1\rangle_{a_1a_2} \), and then conclude that the two pairs are in case \( i \neq j \). On the other hand, for \( n \neq 0 \), two signal photons state is \( \sqrt{2} (|0\rangle, 2)_{a_1a_2} + |2, 0\rangle_{a_1a_2} \) up to a phase shift \( \pi \), which can be erased according to the classical feed-forward result \( n \) of the projection \( |n\rangle \langle n| \), and then claim that the two pairs are in case \( i = j \).

Notice that interference occur, in principle, as two photons coming from two different pairs arrive at a PBS. For the first experimental scheme of four-photon GHZ state [20] or the preparation of four-photon twelve-qubit hyperentangled state [21], only fourfold coincidence detections or QND are used and thus the cases \( i = j \) are discarded. Surprisingly, in our scheme the two cases are all collected. Considering the probabilities for two sources emit one pair each and one source emit two pairs are the same order of magnitude [14] and near deterministic photon number-resolving measurement [29], therefore the efficiency of the present scheme can be increased compared to previous schemes.

5. Discussion and summary

In summary, we demonstrate a method of preparing and purifying the four-photon GHZ state. The present scheme has several notable features. Firstly, because it contains two cases, that is, two entangled photon pairs emitted in four spatial modes and alternatively only in two spatial modes, our scheme is more efficient than the conventional schemes. Secondly, we design polarization entanglement purification using spatial entanglement and thus there is a powerful error-correcting capability in noisy channels. Thirdly, by putting an H operation (a 45° polarizer) followed by single-photon detectors in the \( \text{HV} \) basis in any one set of detectors (e.g., \( E_4 \), for example), one can also implement preparation for the three-photon GHZ state. Finally, the strength of the non-linearities required for the process of photon number-resolving detection are orders of magnitude weaker than the threshold of becoming practical with electromagnetically induced transparency (i.e. \( \theta \sim 10^{-2} \)). In a word, we present an efficient preparation and purification scheme for the four-photon GHZ state with current technology. Also, the present scheme can be easily extended to preparing some other multi-
photon entangled states and some other degrees of freedom, frequency degree of freedom, for example.

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