Efficient and flexible generation of entangled qudits with cross
phase modulation

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Abstract

In this paper, we provide a simple but powerful module to generate entangled qudits. This
module assisted with cross-Kerr nonlinearity is available to the entangled qudits generation with
arbitrary dimension, and it could work well even when the two independent qudits lose the same
number of single photons. Moreover, with the cascade uses of modules, the deterministic generation
but with nonidentical forms of entangled qudits is possible.

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I. INTRODUCTION

Quantum entanglement plays an important role in the research of quantum information communication and computing. It has been used widely in various quantum information tasks, such as quantum teleportation [1], quantum dense coding [2], etc. With the development of quantum information, more and more people turn their attention to high dimension quantum state and entangled state, since higher dimension means stronger nonlocality and much more powerful capability for quantum information processing. The application of qudits, as well as entangled qudits, could increase the security of quantum cryptography [3–9] and the efficiency of quantum logic gates [10, 11]. In this sense, how to create qudits and entangled qudits efficiently is worth discussing. In optical systems, various schemes are provided, such as orbital angular momentum entangled qutrits [12, 13], pixel entanglement [14–16], energy-time entangled qutrits and time-bin entanglement [17, 18], polarization degree of freedom of multi-photon qudits and entangled qudits [19–29], etc.

Here, we will only focus on the generation of entangled polarization qudits and we adopt the definition of qudit as $|j\rangle_n \equiv |(n - j - 1)H, jV\rangle$, for $j = 0, \cdots, n - 1$, where $n$ is the dimension of qudit, and $H$ and $V$ represent the horizontal and vertical polarizations. In other words, the qudits are represented by the polarizations of $n - 1$ photons in the same spatial and temporal mode. Almost all the previous proposals of polarization entangled qudits are processed with only linear optical elements. Therefore we could appreciate the robustness against decoherence of optical system and the ease of single photon operation [30]. However, on the other hand, we have to encounter a serious problem that the two-particle operations fail most of the time. Unfortunately, this probability problem is inevitable in linear optical quantum information processing, including the generation of entangled qudits [26, 28, 29]. For example, the success probability of entangled qutrits generation with linear optical elements is 3/16 in Ref. [28] and 1/3 in Ref. [26], respectively.

Though various theoretical schemes based on linear optics are considered to be experimental feasible, however, a realistic quantum information task may include many qubits and many operations, and then the probability problem will obviously reduce the possibility of a theoretical scheme. Therefore, a theoretical scheme with high efficiency or a deterministic scheme is expected, which is the principle motivation of this paper. Exactly, a deterministic scheme is possible, if assisted with a new technology, called cross-phase modulation
approach. This technology bases on the weak cross-Kerr nonlinearity and has been used widely in quantum information processing tasks recently. It enables the deterministic quantum computation with qubits \[31–36\], creation of long-distance entanglement \[37, 38\], the universal single-particle operation of qutrit \[39\], etc. Briefly, the XPM approach bases on the interaction between a Fock state \(|n\rangle\) and a coherent state \(|\alpha\rangle\), resulting in the transformation \(|n\rangle|\alpha\rangle \rightarrow |n\rangle|\alpha e^{i\theta}\rangle\), where the phase shift of coherent state is determined by the photon number of the Fock state. Assisted with this XPM approach, we will show the generation of entangled qudits could be efficient and flexible. To some extent, this scheme is robust against photon loss, then the loss of the photon will only result in the reduction of the dimension. Furthermore, the deterministic generation could be possible with further operation, though the output forms of entangled qudits are not identical.

The rest of the paper is organized as follows. In Section II, we introduce a simple module, which could be used to create entangled qutrits from independent qutrits. In Section III, we will show that this module is available for entangled qudits generation as well. In order to generate entangled qutrits or entangled qudits more efficiently, or even deterministically, we modify the module and then use cascade modules to achieve this goal in Section IV. Section V is for discussion and conclusion remark.

II. GENERATION OF ENTANGLED QUTRITS

Firstly, we consider the generation of entangled qutrits, which is shown in Fig.1. This approach enables the transformation from two independent qutrits to entangled qutrits, and can be applied to the entangled qudits generation as well (see Sec. III). Suppose the two independent qutrits are initially prepared as

\[
|\psi_1\rangle = \alpha_0|0\rangle_3 + \alpha_1|1\rangle_3 + \alpha_2|2\rangle_3, \\
|\psi_2\rangle = \beta_0|0\rangle_3 + \beta_1|1\rangle_3 + \beta_2|2\rangle_3, \tag{1}
\]

where \(\sum_{i=0}^{2} |\alpha_i| = 1\) and \(\sum_{i=0}^{2} |\beta_i| = 1\). These independent qutrits with some special forms could be created by higher-order parametric down-conversion process (two single photons appearing in each of the two output modes) \[27\], or the Hong-Ou-Mandal (HOM) interference of two single-photon qubits \[40\]. Alternatively, the independent qutrits with arbitrary forms
FIG. 1: A simple module and its application to the entangled qutrits generation. Two independent qutrits are injected into two PBSs and interacted with two qubus beams $|\alpha\rangle |\alpha\rangle$ as indicated. After one more 50:50 BS, an ideal PNND is used to distinguish the vacuum state from non-vacuum state. If the detection is $n = 0$, the entangled qutrits are finally created. This scheme is suitable for the generation of entangled qudit as well. For details, see text.

could be created by the transformation from spatial encoded photonic qutrits to biphotonic qutrits as shown in Ref. [39].

At first, the two input states are injected into two polarizing beam splitters (PBSs) respectively. If the qutrit is in state $|0\rangle_3$, both photons will pass through the PBS; if it is in state $|1\rangle_3$, one photon will pass through and the other photon will be reflected; while if it is in state $|2\rangle_3$, both photons will be reflected. After that, we introduced two quantum bus (qubus) beams $|\alpha\rangle |\alpha\rangle$ and then coupled to the corresponding photonic modes as depicted in Fig.1. Suppose the XPM phase shifts induced by the couplings are all $\theta$, and then each mode of the first qutrit will evolve as follows,

$$
|0\rangle_3 |\alpha\rangle |\alpha\rangle \rightarrow |0\rangle_3 |\alpha\rangle |\alpha e^{i2\theta}\rangle,
$$

$$
|1\rangle_3 |\alpha\rangle |\alpha\rangle \rightarrow |1\rangle_3 |\alpha e^{i\theta}\rangle |\alpha e^{i\theta}\rangle,
$$

$$
|2\rangle_3 |\alpha\rangle |\alpha\rangle \rightarrow |2\rangle_3 |\alpha e^{i2\theta}\rangle |\alpha\rangle.
$$

(2)

Exchanging the orders of output qubus beams in above equations, they are the evolutions
of the second qutrit modes. Then the following state could be achieved,

\[
\begin{align*}
& (\alpha_0 \beta_0 |0\rangle_3 |0\rangle_3 + \alpha_1 \beta_1 |1\rangle_3 |1\rangle_3 + \alpha_2 \beta_2 |2\rangle_3 |2\rangle_3) |\alpha e^{i2\theta}\rangle |\alpha e^{i2\theta}\rangle \\
& + (\alpha_0 \beta_1 |0\rangle_3 |1\rangle_3 + \alpha_1 \beta_2 |1\rangle_3 |2\rangle_3) |\alpha e^{i\theta}\rangle |\alpha e^{i3\theta}\rangle \\
& + (\alpha_1 \beta_0 |1\rangle_3 |0\rangle_3 + \alpha_2 \beta_1 |2\rangle_3 |1\rangle_3) |\alpha e^{i3\theta}\rangle |\alpha e^{i\theta}\rangle \\
& + \alpha_0 \beta_2 |0\rangle_3 |2\rangle_3 |\alpha\rangle |\alpha e^{i4\theta}\rangle + \alpha_2 \beta_0 |2\rangle_3 |0\rangle_3 |\alpha e^{i4\theta}\rangle |\alpha\rangle.
\end{align*}
\]

Next, a 50:50 beam splitter (BS) implementing the transformation \(|\alpha_1\rangle|\alpha_2\rangle \rightarrow |\frac{\alpha_1 - \alpha_2}{\sqrt{2}}\rangle |\frac{\alpha_1 + \alpha_2}{\sqrt{2}}\rangle\) will transform the above state to

\[
\begin{align*}
& (\alpha_0 \beta_0 |0\rangle_3 |0\rangle_3 + \alpha_1 \beta_1 |1\rangle_3 |1\rangle_3 + \alpha_2 \beta_2 |2\rangle_3 |2\rangle_3) |0\rangle |\sqrt{2} \alpha e^{i2\theta}\rangle \\
& + (\alpha_0 \beta_1 |0\rangle_3 |1\rangle_3 + \alpha_1 \beta_2 |1\rangle_3 |2\rangle_3) |\alpha_+\rangle |\alpha_+\rangle \\
& + (\alpha_1 \beta_0 |1\rangle_3 |0\rangle_3 + \alpha_2 \beta_1 |2\rangle_3 |1\rangle_3) |\alpha_+\rangle |\alpha_-\rangle \\
& + \alpha_0 \beta_2 |0\rangle_3 |2\rangle_3 |\alpha_-\rangle |\alpha_+\rangle + \alpha_2 \beta_0 |2\rangle_3 |0\rangle_3 |\alpha_-\rangle |\alpha_+\rangle.
\end{align*}
\]

where \(|\alpha_\pm\rangle = |\frac{\alpha e^{i\theta} \pm \alpha e^{i3\theta}}{\sqrt{2}}\rangle\) and \(|\alpha_\pm\rangle = |\frac{\alpha_\pm \alpha e^{i4\theta}}{\sqrt{2}}\rangle\). Finally, the following desired entangled qutrit (unnormalized),

\[
\alpha_0 \beta_0 |0\rangle_3 |0\rangle_3 + \alpha_1 \beta_1 |1\rangle_3 |1\rangle_3 + \alpha_2 \beta_2 |2\rangle_3 |2\rangle_3,
\]

could be achieved, if the vacuum state \(|0\rangle\) could be distinguished from the components \(|\pm \alpha_-\rangle\) and \(|\pm \alpha_-\rangle\). Exactly, an ideal photon number non-resolving detector (PNND) (on/off detector with quantum efficiency \(\eta = 1\)) is available to complete the discrimination. The success probability is \(\sum_{i=0}^{2} |\alpha_i \beta_i|^2\). Especially, if \(\alpha_i = \beta_i = \frac{1}{\sqrt{3}} (i = 0, 1, 2)\), the output state is the maximal entangled qutrit with the success probability \(\frac{1}{3}\). The error probability of this maximal entangled qutrit caused by the overlap of the coherent components \(|0\rangle\), \(|\pm \alpha_-\rangle\), and \(|\pm \alpha_-\rangle\) is

\[
P_E = \frac{4}{9} e^{-|\alpha|^2 \sin^2 \theta} + \frac{2}{9} e^{-|\alpha|^2 \sin^2 2\theta}.
\]

Even if \(\theta \ll 1\) for the weak cross-Kerr nonlinearity, the error probability will tend to 0 given \(|\alpha| \sin \theta \gg 1\) and \(|\alpha| \sin 2\theta \gg 1\).


III. GENERATION OF ENTANGLED QUDITS

Actually, the above scheme could be generalized to the generation of entangled qudits straightly. The generation processes are the same, and suppose the initial input state is the following product state,

$$\sum_{i=0}^{n-1} \alpha_i |i\rangle_n \otimes \sum_{j=0}^{n-1} \beta_j |j\rangle_n.$$  (7)

After the input state interacts with the two qubus beams $|\alpha\rangle |\alpha\rangle$ as depicted in Fig.1, the following state could be achieved,

$$\sum_{i=0}^{n-1} \alpha_i \beta_i |i\rangle_n |i\rangle_n |\alpha e^{i\theta}\rangle |\alpha e^{i\theta}\rangle + \mathcal{C},$$  (8)

where $\mathcal{C}$ denotes the other cross components that the qubus beams pick different phase shifts. One more 50:50 BS, associated with an ideal PNND placing on one of the output modes, will yield the following target state (unnormalized),

$$\sum_{i=0}^{n-1} \alpha_i \beta_i |i\rangle_n |i\rangle_n.$$  (9)

The total success probability is $\sum_{i=0}^{n-1} |\alpha_i \beta_i|^2$. If $\alpha_i = \beta_i = \frac{1}{\sqrt{n}} (i = 0, ..., n-1)$, the output state is the maximal entangled qudit $\sum_{i=0}^{n-1} \frac{1}{\sqrt{n}} |i\rangle_n |i\rangle_n$, and the success probability is $\frac{1}{n}$, reducing linearly with the increasing of dimension.

All the generation processes are the same for entangled qudit. In other words, our scheme is suitable for any qudit. The flexibility of the setup in generating any entangled qudits will be maximized. An arbitrary entangled qudits could be efficiently generated by a single module in this new approach. Moreover, to some extent, this approach is robust against photon loss, which is a realistic problem must be dealt with. If each input state respectively loses the same number of single photons ($m$), the generation will be still success, though the level of dimension is reduced to $n - m$, which is another advantage of our approach.

IV. DETERMINISTIC GENERATION OF ENTANGLED QUTRITS

The above scheme is still probabilistic. Since the single photons of the qutrit or qudit are in the same spatial-temporal mode, then the operations applied to qutrit or qudit are
FIG. 2: Deterministic generation of entangled qutrits with two cascade modified generation modules. In the modified generation module shown in the dash-dotted line, an additional phase shift $-2\theta$ is, respectively, applied to two qubus beams after the interactions. In order to improve the generation efficiency of entangled qutrits, we replace the ideal PNND by a QND module, which could be used to realize the projection $|n\rangle \langle n|$, and the detections are used to control the switch (S) through the classical feedforward. If the detection is $n = 0$, the generation is successful and the output modes are switched into spatial modes 1 and 4; while if the detection is $n \neq 0$, the output modes are switched into the spatial modes 2 and 3 to be operated further by the second generation module associated with a bit flip operation placed on spatial mode 3. Finally, the entangled qutrits with other forms (see Eq. (17) and Eq. (18)) could be achieved in the output modes 5, 8 or 6, 7. Usually nondeterministically, even assisted with XPM [39]. Nevertheless, it is possible to generate the entangled qutrits and qudits deterministically with further operations, though the output forms are not identical. Here we use the generation of entangled qutrits as an example, which is shown in Fig. 2.

Similarly, the input states of Eq. (1) interact with two qubus beams as depicted in the dash-dotted line in Fig. 2, and then the state in Eq. (3) could be achieved. After that, a phase shift $-2\theta$ is respectively applied to the two qubus beams, which will evolve the state
in Eq. (3) to the follows,

\[ (\alpha_0\beta_0|0\rangle_3|0\rangle_3 + \alpha_1\beta_1|1\rangle_3|1\rangle_3 + \alpha_2\beta_2|2\rangle_3|2\rangle_3)|\alpha\rangle|\alpha\rangle \]
\[ + (\alpha_0\beta_1|0\rangle_3|1\rangle_3 + \alpha_1\beta_2|1\rangle_3|2\rangle_3)|\alpha e^{-i\theta}\rangle|\alpha e^{i\theta}\rangle \]
\[ + (\alpha_1\beta_0|1\rangle_3|0\rangle_3 + \alpha_2\beta_1|2\rangle_3|1\rangle_3)|\alpha e^{i\theta}\rangle|\alpha e^{-i\theta}\rangle \]
\[ + \alpha_0\beta_2|0\rangle_3|2\rangle_3|\alpha e^{i2\theta}\rangle|\alpha e^{-i2\theta}\rangle \]
\[ + \alpha_2\beta_0|2\rangle_3|0\rangle_3|\alpha e^{i2\theta}\rangle|\alpha e^{-i2\theta}\rangle. \]  

(10)

Next, one more 50:50 BS will transform the above state to

\[ (\alpha_0\beta_0|0\rangle_3|0\rangle_3 + \alpha_1\beta_1|1\rangle_3|1\rangle_3 + \alpha_2\beta_2|2\rangle_3|2\rangle_3)|0\rangle|\sqrt{2}\alpha\rangle \]
\[ + (\alpha_0\beta_1|0\rangle_3|1\rangle_3 + \alpha_1\beta_2|1\rangle_3|2\rangle_3)|-i\sqrt{2}\alpha \sin \theta \rangle|\sqrt{2}\alpha \cos \theta \rangle \]
\[ + (\alpha_1\beta_0|1\rangle_3|0\rangle_3 + \alpha_2\beta_1|2\rangle_3|1\rangle_3)|i\sqrt{2}\alpha \sin \theta \rangle|\sqrt{2}\alpha \cos \theta \rangle \]
\[ + \alpha_0\beta_2|0\rangle_3|2\rangle_3|-i\sqrt{2}\alpha \sin 2\theta \rangle|\sqrt{2}\alpha \cos 2\theta \rangle \]
\[ + \alpha_2\beta_0|2\rangle_3|0\rangle_3|i\sqrt{2}\alpha \sin 2\theta \rangle|\sqrt{2}\alpha \cos 2\theta \rangle. \]

(11)

Now, we replace the ideal PNND in Fig.1 by the projection $|n\rangle \langle n|$, which could be realized by the quantum nondemolition detection (QND) module nearly deterministically, even with the common PNND (quantum efficiency $\eta < 1$). The detections will project the above state into two subspaces. If the detection is $n = 0$, the following state could be achieved (unnormalized),

\[ \alpha_0\beta_0|0\rangle_3|0\rangle_3 + \alpha_1\beta_1|1\rangle_3|1\rangle_3 + \alpha_2\beta_2|2\rangle_3|2\rangle_3. \]

(12)

Through the classical feedforward, the above output modes are switched to spatial modes 1 and 4. While if the detection is $n \neq 0$, the output state could be described as the following unnormalized form,

\[ c_1 (\alpha_0\beta_1|0\rangle_3|1\rangle_3 + \alpha_1\beta_2|1\rangle_3|2\rangle_3)|\sqrt{2}\gamma \rangle \]
\[ + c_2 (\alpha_1\beta_0|1\rangle_3|0\rangle_3 + \alpha_2\beta_1|2\rangle_3|1\rangle_3)|\sqrt{2}\gamma \rangle \]
\[ + (c_3\alpha_0\beta_2|0\rangle_3|2\rangle_3 + c_4\alpha_2\beta_0|2\rangle_3|0\rangle_3)|\sqrt{2}\gamma \rangle, \]

(13)

where

\[ c_1 = e^{-2|\alpha|^2 \sin^2 \theta / \sqrt{\eta}}, \quad c_2 = e^{in\pi} c_1, \quad c_3 = e^{-2|\alpha|^2 \sin^2 2\theta / \sqrt{\eta}}, \quad c_4 = e^{in\pi} c_3, \]

$\gamma = \alpha \cos \theta$ and $\gamma' = \alpha \cos 2\theta$. These modes are switched to the spatial modes 2 and 3, which will be operated further.
It should be noted here that the qubus beam $|\sqrt{2}\gamma\rangle$ or $|\sqrt{2}\gamma'\rangle$ is still strong enough to be recycled as ancilla, since the XPM phase shift $\theta \ll 1$. On the other hand, the amplitude of the qubus beams is different, but it will not affect the final result (see below). After the first operation, a bit flip operation $\sigma_x$ is placed on the spatial mode 3, yielding the following transformations,

$$
|0\rangle_3 \rightarrow |2\rangle_3, |1\rangle_3 \rightarrow |1\rangle_3, |2\rangle_3 \rightarrow |0\rangle_3.
$$

(14)

Then, the following state could be achieved,

$$
c_1 (\alpha_0\beta_1|0\rangle_3|1\rangle_3 + \alpha_1\beta_2|1\rangle_3|0\rangle_3) |\sqrt{2}\gamma\rangle
+ c_2 (\alpha_1\beta_0|1\rangle_3|2\rangle_3 + \alpha_2\beta_1|2\rangle_3|1\rangle_3) |\sqrt{2}\gamma\rangle
+ (c_3\alpha_0\beta_2|0\rangle_3|0\rangle_3 + c_4\alpha_2\beta_0|2\rangle_3|2\rangle_3) |\sqrt{2}\gamma'\rangle,
$$

(15)

Similar with the processes from Eq. (2) to Eq. (3) and Eq. (10) to Eq. (11), we could achieve the following state,

$$
(c_1\alpha_0\beta_1|0\rangle_3|1\rangle_3 + c_2\alpha_1\beta_0|1\rangle_3|2\rangle_3) |-i\sqrt{2}\gamma\sin\theta\rangle|\sqrt{2}\gamma\cos\theta\rangle
+ (c_1\alpha_1\beta_2|1\rangle_3|0\rangle_3 + c_2\alpha_2\beta_1|2\rangle_3|1\rangle_3) |i\sqrt{2}\gamma\sin\theta\rangle|\sqrt{2}\gamma\cos\theta\rangle
+ (c_3\alpha_0\beta_2|0\rangle_3|0\rangle_3 + c_4\alpha_2\beta_0|2\rangle_3|2\rangle_3) |0\rangle|\sqrt{2}\gamma'\rangle.
$$

(16)

Finally, we use the projection $|n\rangle \langle n|$ by the QND module to detect the first qubus beam. If $n' = 0$, we could achieve the following state (unnormalized),

$$
c_3\alpha_0\beta_2|0\rangle_3|0\rangle_3 + c_4\alpha_2\beta_0|2\rangle_3|2\rangle_3,
$$

(17)

from the spatial modes 5 and 8. The unnecessary phase shift $e^{in\pi}$ between the above two coefficients $c_3$ and $c_4$ could be removed by the single photon operation $\begin{pmatrix} 1 \\ e^{-in\pi/2} \end{pmatrix}$ performed on one of two qutrits. On the other hand, if the result is $n' \neq 0$, we could achieve the following state (unnormalized),

$$
c_1\alpha_0\beta_1|0\rangle_3|1\rangle_3 + c_2\alpha_1\beta_0|1\rangle_3|2\rangle_3
+ e^{in'\pi} (c_1\alpha_1\beta_2|1\rangle_3|0\rangle_3 + c_2\alpha_2\beta_1|2\rangle_3|1\rangle_3),
$$

(18)
from the spatial modes 6 and 7. Similarly, the different phase shifts between each component could be removed, according to the results $n$ and $n'$. For example, if $n$ is odd and $n'$ is even, then two single photon operations $\begin{pmatrix} 1 \\ e^{-i\pi/2} \end{pmatrix}$ respectively performed on the two qutrits could remove these phase shifts.

In the above content, we show two cascade operations, which could project the input independent qutrits into three forms of entangled qutrits with different success probability. In other words, the generation of entangled qutrits from two independent qutrits could be deterministic, though the forms of entangled qutrits depend on the detections of two QND modules. The situation will be similar, if we treat the independent qudits following the same method. In the case of $n$ dimension quantum state, $n - 1$ cascade operations will project the input product qudits into a series of entangled qudits with different forms.

V. DISCUSSION AND CONCLUSION

In this paper, we propose a simple module to generate entangled qudits. This module is available for any cases and enables deterministic generation by cascade use. There are other proposals suggested for the entangled qudits generation with linear optical elements. A heralded two-qutrit entangled state could be generated through the HOM interferences of two heralded Bell pairs with the success probability $3/16$ \[28\]. Compared with their scheme, our scheme with one use of module succeeds with the probability $1/3$ for maximal entangled qutrits. Another proposal suggests generating entangled qudits through the interference of two independent qudits on a PBS, associated with the ideal photon number resolving QND detection \[26\]. The success probability is the same as our scheme. However, the requirement of that QND detection is not realistic, at least with current experimental technology. Compared with it, only the ideal PNND is necessary for our scheme, which is more realistic. In addition, with the theoretical realistic QND module proposed in Refs. \[35–38\], the further operation and the deterministic generation are possible, which is significantly better than the former works.

Except of the common linear optical elements, the core element of our scheme is the weak cross-Kerr nonlinearity. Though we treat it in idealized single-mode picture, it still works well when multi-mode effect is taken into accounting. It had been theoretically demonstrated
that a small conditional phase shift $\theta \ll 1$ with high fidelity could be achieved through the interaction between continuous-mode photonic pulses (a single photon and a coherent state) [41]. In other words, the single-mode approximation in the weak nonlinearity regime is valid, and then our scheme is feasible with the current experimental technology.

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