



RETRACTED: Efficient Concentration Protocols for the Single-Photon Entanglement State with Polarization Feature

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We propose two efficient entanglement concentration protocols (ECPs) for arbitrary less-entangled single-photon entanglement state, in which the photon qubit has the polarization feature. The first ECP is in linear optics, and the second ECP is in nonlinear optics. The two ECPs have some attractive advantages. First, they can preserve the polarization feature of the photon qubit, while all the other existing ECPs for single photon state cannot achieve this goal. Second, they only require one pair of less-entangled single-photon entanglement state and some auxiliary single photons. Third, they only require local operations. Especially, the second ECP can be used repeatedly, which can increase its success probability largely. Based on above properties, our two ECPs, especially the second one may be useful in current and future quantum communication.

Keywords: single-photon entanglement, entanglement concentration, cross-Kerr nonlinearity, variable beam splitter

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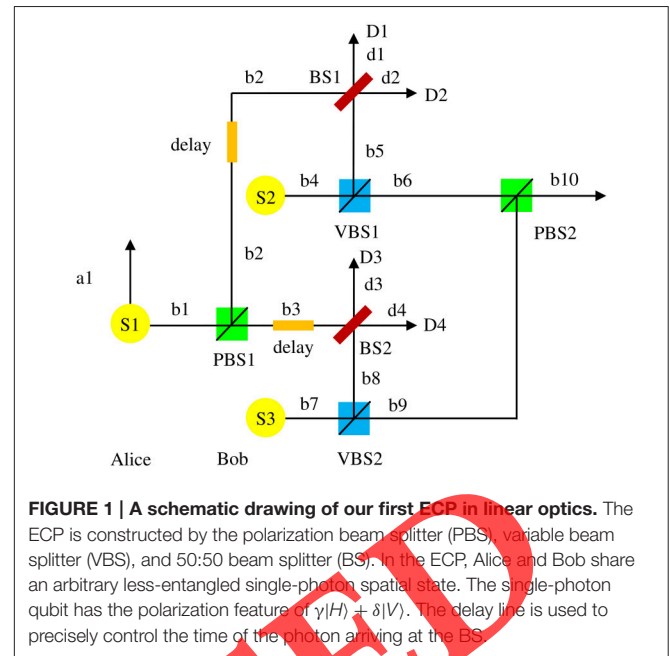
1. INTRODUCTION

Entanglement is central to almost all the protocols of practical quantum communication and computation tasks, such as the quantum cryptography [1], quantum teleportation [2–5], quantum secure direct communication [6–8], quantum repeaters [9, 10], quantum dense coding [11], entanglement-based quantum key distribution [12–14], and some other quantum communication applications [15–19]. During the past decade, a large number of single-particle and multi-particle entanglement states have been successfully generated [20–23]. In various applications, photons are the best long-range carriers of quantum information, for photons have long decoherence time, and are relatively easy to manipulate. The single-photon entanglement (SPE) with the form of $\frac{1}{\sqrt{2}}(|0, 1\rangle_{AB} + |1, 0\rangle_{AB})$ is the simplest entanglement form. It describes a superposition state, in which the single photon is in two different modes A and B. SPE has wide applications in the quantum information field. For example, the well known Duan-Lukin-Cirac-Zoller (DLCZ) repeater protocol [24] requires the quantum state with the form of $\frac{1}{\sqrt{2}}(|e\rangle_A |g\rangle_B + |g\rangle_A |e\rangle_B)$, where the $|e\rangle$ and $|g\rangle$ represent the excited state and the ground state of the atomic ensembles, respectively. In 2005, Chou et al. observed the spatial entanglement between two atomic ensembles located in distance. It is essentially the creation of the single-photon spatial entanglement by storing the entanglement into the atomic-ensemble-based quantum memory [25]. In 2012, Gottesman et al. proposed an interesting protocol for constructing an interferometric telescope based on the SPE

[26]. With the help of the SPE, the protocol has the potential to eliminate the baseline length limit, and realize the interferometers with arbitrarily long baselines in principle. Unfortunately, in the practical applications, the environmental noise can lead to the decoherence of the photonic quantum system, which may make the maximally entangled state degrade to a mixed state or a pure less-entangled state. The degraded quantum state cannot be used to set up the high-quality quantum entanglement channel [24]. Therefore, we need to recover the mixed state or the pure less-entangled state into the maximally entangled state prior to the applications.

The entanglement purification is an efficient method to recover the mixed state into the maximally entangled state, which has been widely researched [27–37]. The entanglement concentration, which will be detailed here, can be used to recover the pure less-entangled state into the maximally entangled state [38–68]. In 1996, Bennett et al. proposed the first entanglement concentration protocol, the Schmidt projection method [38]. It is a great start for the entanglement concentration. Later, the ECPs based on entanglement swapping [39] and the unitary transformation [40] were proposed successively. In 2001, Zhao et al. and Yamamoto et al. put forward two similar ECPs independently with linear optical elements [41, 42], both of which were realized in experiment. In 2008, the group of Sheng improved these two ECPs by adopting the cross-Kerr nonlinearities to construct the nondemolition measurement gate [43]. In 2010, the first ECP for SPE was proposed by Sheng et al. In the ECP, we can distill one pair of maximally entangled single-photon state from two pairs of less-entangled single-photon states [44]. Later, Sheng proposed two efficient single-photon assisted ECPs for arbitrary less-entangled two-photon entanglement state and W state, respectively [45, 46]. In 2013 and 2014, inspired by the above single-photon assisted ECPs, we proposed the improved ECPs for arbitrary less-entangled SPE and single-photon multi-mode W state [47, 48]. Actually, for a photon qubit, the information can be encoded in the spatial modes and the orthogonal polarization mode simultaneously. However, all the previous ECPs for single photon spatial entanglement cannot preserve the polarization feature of the photon qubit. In 2013, the group of Kocsis proposed an efficient heralded amplification protocol for a single photon qubit [69]. Different with the previous amplification protocols for the single photon qubits [70–74], the protocol designed a coherent two-mode amplifier, and can realize the heralded noiseless linear amplification of a single-photon qubit encoded in the polarization state.

Based on the attractive work in Kocsis et al. [69], in the paper, we put forward two efficient ECPs for the single photon spatial entanglement. The first ECP is in linear optics and the second one is nonlinear. Both of them not only can recover arbitrary less-entangled single-photon spatial state into the maximally entangled single-photon spatial state, but also can preserve the polarization feature of the photon qubit. Especially, with the help of cross-Kerr nonlinearities, the second ECP can be repeated to increase the success probability. Based on these attractive properties, our two ECPs, especially the second one may be useful in current and future quantum information tasks.



The paper is organized as follows: in Section 2, we explain the first linear ECP. In Section 3, we explain the second nonlinear ECP. In Section 4, we make a discussion and summary.

2. THE FIRST ECP FOR THE SINGLE-PHOTON SPATIAL ENTANGLEMENT

The basic principle of our first ECP is shown in **Figure 1**. We suppose a single photon source S1 emits a single photon, and sends it to Alice and Bob in the spatial mode a1 and b1, respectively. Due to the channel noise, it creates a less-entangled single-photon spatial state as:

$$|\phi_1\rangle_{a1b1} = \alpha|1,0\rangle_{a1b1} + \beta|0,1\rangle_{a1b1}, \quad (1)$$

where α and β are the coefficients of the initial entangled state, $|\alpha|^2 + |\beta|^2 = 1$. We consider the polarization of the single-photon qubit can be written as:

$$|\phi'_1\rangle = \gamma|H\rangle + \delta|V\rangle, \quad (2)$$

where $|H\rangle$ and $|V\rangle$ represent the horizontal and vertical polarization of the single photon. γ and δ are the coefficients of the polarization state, $|\gamma|^2 + |\delta|^2 = 1$. Therefore, the SPE can be described as:

$$|\Phi_1\rangle_{a1b1} = |\phi_1\rangle_{a1b1} \otimes |\phi'_1\rangle = \alpha\gamma|1_H,0\rangle_{a1b1} + \alpha\delta|1_V,0\rangle_{a1b1} + \beta\gamma|0,1_H\rangle_{a1b1} + \beta\delta|0,1_V\rangle_{a1b1}. \quad (3)$$

The whole concentration operation can be performed by Bob alone. Bob first makes the photon in the b1 mode pass through the polarization beam splitter (PBS), here named PBS1, which

can fully transmit the photon in $|H\rangle$ and reflect the photon in $|V\rangle$. It can be easily found that the item $|1_V\rangle_{b1}$ will make the single photon in the upper spatial mode b2, while the item $|1_H\rangle_{b1}$ will make the single photon in the lower spatial mode b3. In this way, after PBS1, $|\Phi_1\rangle_{a1b1}$ in Equation (3) can be divided into:

$$|\Phi_1^+\rangle_{a1b2} = \alpha|1_V, 0\rangle_{a1b2} + \beta|0, 1_V\rangle_{a1b2}, \quad (4)$$

with the probability of $|\delta|^2$, and

$$|\Phi_1^-\rangle_{a1b3} = \alpha|1_H, 0\rangle_{a1b3} + \beta|0, 1_H\rangle_{a1b3}, \quad (5)$$

with the probability of $|\gamma|^2$.

Afterwards, $|\Phi_1^+\rangle_{a1b2}$ and $|\Phi_1^-\rangle_{a1b3}$ can be individually concentrated by the similar process. Here, we first explain the concentration process of $|\Phi_1^+\rangle_{a1b2}$. A single photon source S2 emits an auxiliary single photon in $|V\rangle$, and sends it to Bob in the spatial mode b4. Bob makes it pass through a variable beam splitter (VBS) with the transmittance of t_1 , here named VBS1. After VBS1, the quantum state of the auxiliary single photon can be written as:

$$|\Phi_2\rangle_{b5b6} = \sqrt{1-t_1}|1_V, 0\rangle_{b5b6} + \sqrt{t_1}|0, 1_V\rangle_{b5b6}. \quad (6)$$

In this way, $|\Phi_1^+\rangle_{a1b2}$ combined with $|\Phi_2\rangle_{b5b6}$ can be written as

$$\begin{aligned} |\Phi_3\rangle_{a1b2b5b6} &= |\Phi_1^+\rangle_{a1b2} \otimes |\Phi_2\rangle_{b5b6} \\ &= \alpha\sqrt{1-t_1}|1_V, 0, 1_V, 0\rangle_{a1b2b5b6} \\ &\quad + \alpha\sqrt{t_1}|1_V, 0, 0, 1_V\rangle_{a1b2b5b6} \\ &\quad + \beta\sqrt{1-t_1}|0, 1_V, 1_V, 0\rangle_{a1b2b5b6} \\ &\quad + \beta\sqrt{t_1}|0, 1_V, 0, 1_V\rangle_{a1b2b5b6}. \end{aligned} \quad (7)$$

Then, Bob makes the photons in the b2 and b5 modes pass through a 50:50 beam splitter (BS), here named BS1, which can make:

$$|1\rangle_{b2} = \frac{1}{\sqrt{2}}(|1\rangle_{d1} - |1\rangle_{d2}), \quad |1\rangle_{b5} = \frac{1}{\sqrt{2}}(|1\rangle_{d1} + |1\rangle_{d2}). \quad (8)$$

It is worth noting that we have to precisely control the length of the delay line to ensure that the photons in b2 and b5 modes can arrive at the BS1 simultaneously. In this way, Bob can finally make the HOM interference measurement [75, 76]. After the BS1, $|\Phi_3\rangle_{a1b2b5b6}$ will evolve to:

$$\begin{aligned} |\Phi_3\rangle_{a1b2b5b6} \rightarrow & \frac{\alpha\sqrt{1-t_1}}{\sqrt{2}}|1_V, 1_V, 0, 0\rangle_{a1d1d2b6} \\ & + \frac{\alpha\sqrt{1-t_1}}{\sqrt{2}}|1_V, 0, 1_V, 0\rangle_{a1d1d2b6} \\ & + \alpha\sqrt{t_1}|1_V, 0, 0, 1_V\rangle_{a1d1d2b6} \\ & + \frac{\beta\sqrt{1-t_1}}{\sqrt{2}}|0, 2_V, 0, 0\rangle_{a1d1d2b6} \\ & - \frac{\beta\sqrt{1-t_1}}{\sqrt{2}}|0, 0, 2_V, 0\rangle_{a1d1d2b6} \\ & + \frac{\beta\sqrt{t_1}}{\sqrt{2}}|0, 1_V, 0, 1_V\rangle_{a1d1d2b6} \end{aligned}$$

$$- \frac{\beta\sqrt{t_1}}{\sqrt{2}}|0, 0, 1_V, 1_V\rangle_{a1d1d2b6}. \quad (9)$$

Next, the photons in the d1 and d2 modes are detected by the single-photon detectors D1 and D2, respectively. It can be easily found if only D1 detects exactly one photon, the state in Equation (9) will collapse to:

$$|\Phi_4\rangle_{a1b6} = \alpha\sqrt{1-t_1}|1_V, 0\rangle_{a1b6} + \beta\sqrt{t_1}|0, 1_V\rangle_{a1b6}, \quad (10)$$

while if only D2 detects exactly one photon, the state in Equation (9) will collapse to:

$$|\Phi_5\rangle_{a1b6} = \alpha\sqrt{1-t_1}|1_V, 0\rangle_{a1b6} - \beta\sqrt{t_1}|0, 1_V\rangle_{a1b6}. \quad (11)$$

There is only a phase difference between $|\Phi_5\rangle_{a1b6}$ and $|\Phi_4\rangle_{a1b6}$. $|\Phi_5\rangle_{a1b6}$ can be easily converted to $|\Phi_4\rangle_{a1b6}$ by the phase-flip operation. Especially, if a suitable VBS1 with the transmittance $t_1 = |\alpha|^2$ can be provided, $|\Phi_4\rangle_{a1b6}$ in Equation (10) can evolve to:

$$|\Phi_4\rangle_{a1b6} = \frac{1}{\sqrt{2}}(|1_V, 0\rangle_{a1b6} + |0, 1_V\rangle_{a1b6}). \quad (12)$$

So far, the concentration for $|\Phi_1^+\rangle_{a1b2}$ is completed, and the success probability for getting the state in Equation (12) is $P_1 = 2|\delta|^2|\alpha|^2|\beta|^2$. The concentration process for $|\Phi_1^-\rangle_{a1b3}$ is quite similar with that for $|\Phi_1^+\rangle_{a1b2}$. First, a single photon source S3 emits an auxiliary single photon in $|H\rangle$ and sends it to Bob in the b7 mode. Bob makes this photon pass through the VBS2 with the transmittance of t_2 , which makes it be:

$$|\Phi_6\rangle_{b8b9} = \sqrt{1-t_2}|1_H, 0\rangle_{b8b9} + \sqrt{t_2}|0, 1_H\rangle_{b8b9}. \quad (13)$$

Then Bob also makes the photons in the b3 and b8 modes arrive at the BS2 at the same time by controlling the length of the delay line, which can make:

$$|1\rangle_{b3} = \frac{1}{\sqrt{2}}(|1\rangle_{d3} - |1\rangle_{d4}), \quad |1\rangle_{b8} = \frac{1}{\sqrt{2}}(|1\rangle_{d3} + |1\rangle_{d4}). \quad (14)$$

After the BS2, $|\Phi_1^-\rangle_{a1b3}$ combined with the auxiliary single photon state $|\Phi_6\rangle_{b8b9}$ can evolve to:

$$\begin{aligned} |\Phi_1^-\rangle_{a1b3} \otimes |\Phi_6\rangle_{b8b9} \rightarrow & \frac{\alpha\sqrt{1-t_2}}{\sqrt{2}}|1_H, 1_H, 0, 0\rangle_{a1d3d4b9} \\ & + \frac{\alpha\sqrt{1-t_2}}{\sqrt{2}}|1_H, 0, 1_H, 0\rangle_{a1d3d4b9} \\ & + \alpha\sqrt{t_2}|1_H, 0, 0, 1_V\rangle_{a1d3d4b9} \\ & + \frac{\beta\sqrt{1-t_2}}{\sqrt{2}}|0, 2_H, 0, 0\rangle_{a1d3d4b9} \\ & - \frac{\beta\sqrt{1-t_2}}{\sqrt{2}}|0, 0, 2_H, 0\rangle_{a1d3d4b9} \\ & + \frac{\beta\sqrt{t_2}}{\sqrt{2}}|0, 1_H, 0, 1_H\rangle_{a1d3d4b9} \\ & - \frac{\beta\sqrt{t_2}}{\sqrt{2}}|0, 0, 1_H, 1_H\rangle_{a1d3d4b9}. \end{aligned} \quad (15)$$

Then, Bob detects the photons in the d3 and d4 modes with the single-photon detectors D3 and D4, respectively. If only D3 detects exactly one photon, the state in Equation (15) will collapse to:

$$|\Phi_7\rangle_{a1b9} = \alpha\sqrt{1-t_2}|1_H, 0\rangle_{a1b9} + \beta\sqrt{t_2}|0, 1_H\rangle. \quad (16)$$

If only D4 detects exactly one photon, the state in Equation (15) will collapse to:

$$|\Phi_8\rangle_{a1b9} = \alpha\sqrt{1-t_2}|1_H, 0\rangle_{a1b9} - \beta\sqrt{t_2}|0, 1_H\rangle, \quad (17)$$

which can be converted to $|\Phi_7\rangle_{a1b9}$ by the phase-flip operation.

Under the condition that the transmittance of VBS2 is $t_2 = |\alpha|^2$, $|\Phi_7\rangle_{a1b9}$ in Equation (16) can be rewritten as:

$$|\Phi_7\rangle_{a1b9} = \frac{1}{\sqrt{2}}(|1_H, 0\rangle_{a1b9} + |0, 1_H\rangle). \quad (18)$$

So far, we have successfully concentrated $|\Phi_1^-\rangle_{a1b3}$ to $|\Phi_7\rangle_{a1b9}$, with the probability of $P_2 = 2|\gamma|^2|\alpha|^2|\beta|^2$.

Finally, Bob makes the photons in the b6 and b9 modes pass through the PBS2, then the whole single photon state can evolve to:

$$\begin{aligned} |\Phi_9\rangle_{a1b10} &= \frac{1}{\sqrt{2}}(\gamma|1_H, 0\rangle_{a1b10} + \delta|1_V, 0\rangle_{a1b10} + \gamma|0, 1_H\rangle_{a1b10} \\ &\quad + \delta|0, 1_V\rangle_{a1b10}) \\ &= \frac{1}{\sqrt{2}}(|1, 0\rangle_{a1b10} + |0, 1\rangle_{a1b10}) \otimes (\gamma|H\rangle + \delta|V\rangle). \end{aligned} \quad (19)$$

According to Equation (19), it can be found that by operating our ECP, we can successfully concentrate the less-entangled single-photon state while preserving its polarization characteristic. The total success probability (P) of our ECP can be written as:

$$P = P_1 + P_2 = 2|\alpha|^2|\beta|^2. \quad (20)$$

3. THE SECOND ECP FOR THE SINGLE-PHOTON ENTANGLEMENT

In the second ECP, we adopt the cross-Kerr nonlinearity to construct the quantum nondemolition detector (QND). In this way, before we start to explain the ECP, we first briefly introduce the cross-Kerr nonlinearity. The cross-Kerr nonlinearity has a Hamiltonian of the form:

$$H_{ck} = \hbar\chi\hat{n}_a\hat{n}_b, \quad (21)$$

where $\hbar\chi$ is the coupling strength of the nonlinearity, which depends on the cross-Kerr material. \hat{n}_a and \hat{n}_b are the photon number operators for mode a and mode b, respectively. In the process of cross-Kerr interaction, a laser pulse in the coherent state $|\alpha\rangle$ interacts with the photons through a proper cross-Kerr material. The interaction process can be written as:

$$U_{ck}|\psi\rangle|\alpha\rangle = (\gamma|0\rangle + \delta|1\rangle)|\alpha\rangle \rightarrow \gamma|0\rangle|\alpha\rangle + \delta|1\rangle|\alpha e^{i\theta}\rangle. \quad (22)$$

We note that $|0\rangle$ and $|1\rangle$ are the photon number. If a photon is presented, the interaction will induce the coherent state pick up a phase shift of θ , otherwise, the coherent state pick up no phase shift. In this way, the phase shift is directly proportional to the photon number. As the phase shift can be measured by the homodyne measurement, the photon number in each spatial mode can be detected without destroying the photons. The cross-Kerr nonlinearity provides a good way to construct the QND, which has played an important role in the quantum information field, such as quantum logic gate [77, 78], quantum teleportation [79], entanglement purification and concentration [43–47], and so on [80–91].

In the second ECP, the schematic drawing of the QND is shown in **Figure 2**. It can be found that if a photon is presented in the spatial mode a1, the coherent state $|\alpha\rangle$ will pick up a phase shift of θ , while if a photon is in the spatial mode a2, $|\alpha\rangle$ will pick up a phase shift of $-\theta$.

The schematic drawing of the second ECP is shown in **Figure 3**. We also suppose that Alice and Bob share a less-entangled SPE in the spatial mode a1 and b1 as Equation (3). Bob makes the photon in the b1 mode pass through the PBS1, which leads to the state in Equation (4) in the spatial modes a1 and b2 with the probability of $|\delta|^2$, and the state in Equation (5) in the spatial modes a1 and b3 with the probability of $|\gamma|^2$.

Here, we also take the concentration process for $|\Phi_1^+\rangle_{a1b2}$ in Equation (4) for an example. A single photon source S2 emits an auxiliary photon in the $|V\rangle$ polarization and sends it to Bob in the b4 mode. Bob makes the auxiliary photon pass through VBS1 with the transmittance of t'_1 . After the VBS1, the auxiliary single photon state can be described as:

$$|\psi_2\rangle_{b5b6} = \sqrt{1-t'_1}|1_V, 0\rangle_{b5b6} + \sqrt{t'_1}|0, 1_V\rangle_{b5b6}. \quad (23)$$

Then, Bob makes the photons in the b2 and b5 modes pass through the QND1. In this way, $|\Phi_1^+\rangle_{a1b2}$ combined with the auxiliary single-photon state $|\psi_2\rangle_{b5b6}$ and the coherent state $|\alpha\rangle$ will evolve to:

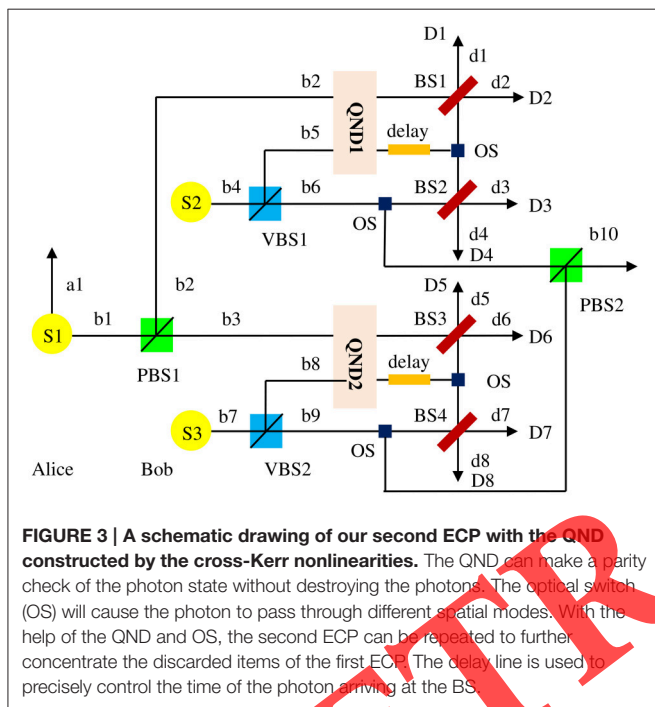
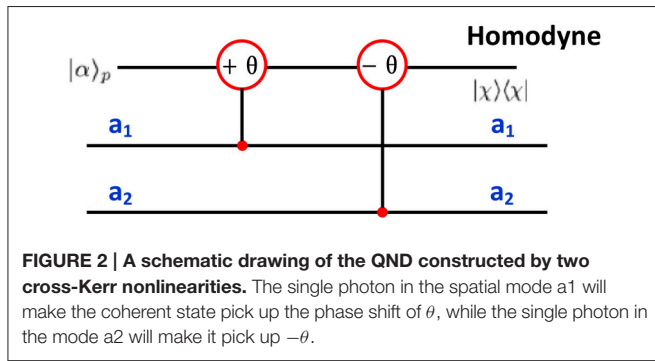
$$\begin{aligned} |\Phi_1^+\rangle_{a1b2} \otimes |\psi_2\rangle_{b5b6} \otimes |\alpha\rangle &\rightarrow \alpha\sqrt{1-t'_1}|1_V, 0, 1_V, 0\rangle_{a1b2b5b6}|\alpha e^{-i\theta}\rangle \\ &\quad + \alpha\sqrt{t'_1}|1_V, 0, 0, 1_V\rangle_{a1b2b5b6}|\alpha\rangle \\ &\quad + \beta\sqrt{1-t'_1}|0, 1_V, 1_V, 0\rangle_{a1b2b5b6}|\alpha\rangle \\ &\quad + \beta\sqrt{t'_1}|0, 1_V, 0, 1_V\rangle_{a1b2b5b6}|\alpha e^{i\theta}\rangle. \end{aligned} \quad (24)$$

As the phase shift of $\pm\theta$ can not be distinguished by the homodyne measurement, Bob selects the items which make the coherent state pick up the phase shift of $\pm\theta$, and the state in Equation (24) will collapse to:

$$\begin{aligned} |\Psi_1^+\rangle_{a1b2b5b6} &= \alpha\sqrt{1-t'_1}|1_V, 0, 1_V, 0\rangle_{a1b2b5b6} \\ &\quad + \beta\sqrt{t'_1}|0, 1_V, 0, 1_V\rangle_{a1b2b5b6}, \end{aligned} \quad (25)$$

with the probability of:

$$P^+ = |\delta|^2[|\alpha|^2(1-t'_1) + |\beta|^2t'_1]. \quad (26)$$



Then, Bob makes the photons in the b2 and b5 modes enter the BS1 simultaneously with the help of the optical switch (OS1) and the delay line. After the BS1, $|\Psi_1^+\rangle_{a1b2b5b6}$ will evolve to:

$$\begin{aligned} |\Psi_2^+\rangle_{a1d1d2b6} = & \alpha\sqrt{1-t_1'}|1_V, 1_V, 0, 0\rangle_{a1d1d2b6} \\ & + \alpha\sqrt{1-t_1'}|1_V, 0, 1_V, 0\rangle_{a1d1d2b6} \\ & + \beta\sqrt{t_1'}|0, 1_V, 0, 1_V\rangle_{a1d1d2b6} \\ & - \beta\sqrt{t_1'}|0, 0, 1_V, 1_V\rangle_{a1d1d2b6}. \end{aligned} \quad (27)$$

Finally, the photons in the d1 and d2 modes are detected by the single-photon detector D1 and D2, respectively. If D1 detects exactly one photon, $|\Psi_2^+\rangle_{a1d1d2b6}$ will collapse to:

$$|\Psi_3^+\rangle_{a1b6} = \alpha\sqrt{1-t_1'}|1_V, 0\rangle_{a1b6} + \beta\sqrt{t_1'}|0, 1_V\rangle_{a1b6}, \quad (28)$$

while if the D2 detects exactly one photon, $|\Psi_2^+\rangle_{a1d1d2b6}$ will collapse to:

$$|\Psi_4^+\rangle_{a1b6} = \alpha\sqrt{1-t_1'}|1_V, 0\rangle_{a1b6} - \beta\sqrt{t_1'}|0, 1_V\rangle_{a1b6}. \quad (29)$$

If they obtain $|\Psi_4^+\rangle_{a1b6}$, Alice or Bob can convert it to $|\Psi_3^+\rangle_{a1b6}$ by the phase-flip operation.

Based on Equation (28), if the transmittance of VBS1 meets $t_1' = |\alpha|^2$, Equation (28) can be converted to Equation (12). So far, the concentration process for $|\Phi_1^+\rangle_{a1b2}$ in Equation (4) is completed, and $|\Phi_1^+\rangle_{a1b2}$ can be finally converted to the state in Equation (12) with the success probability of:

$$P^+ = 2|\delta|^2|\alpha|^2|\beta|^2. \quad (30)$$

The concentration process for $|\Phi_1^-\rangle_{a1b3}$ in Equation (5) is quite similar. The single photon source S3 emits an auxiliary photon in $|H\rangle$ and sends it to Bob in the b7 mode. Based on the concentration steps described above, Bob firstly makes the auxiliary photon pass through the VBS2 with the transmittance of t_1'' . Then, he lets the photons in the b3 and b8 modes enter the QND2 and selects the items which make the coherent state take a phase shift of $\pm\theta$. In this way, he can finally obtain:

$$\begin{aligned} |\Psi_1^-\rangle_{a1b3b8b9} = & \alpha\sqrt{1-t_1''}|1_H, 0, 1_H, 0\rangle_{a1b3b8b9} \\ & + \beta\sqrt{t_1''}|0, 1_H, 0, 1_H\rangle_{a1b3b8b9}. \end{aligned} \quad (31)$$

In order to get the maximally entangled single photon state, Bob makes the photons in the b3 and b8 modes enter the BS3 simultaneously, and then detects the output photons by the single photon detector D5 and D6. Under the cases that D5 or D6 exactly detects one photon, $|\Psi_1^-\rangle_{a1b3b8b9}$ in Equation (31) can finally evolve to

$$|\Psi_2^-\rangle_{a1b9} = \alpha\sqrt{1-t_1''}|1_H, 0\rangle_{a1b9} + \beta\sqrt{t_1''}|0, 1_H\rangle_{a1b9}. \quad (32)$$

If a suitable VBS2 with $t_1'' = |\alpha|^2$ can be provided, $|\Psi_2^-\rangle_{a1b9}$ in Equation (32) can be ultimately converted to the state in Equation (18). Until now, the concentration process for Equation (5) is completed, and its success probability is:

$$P^- = 2|\gamma|^2|\alpha|^2|\beta|^2. \quad (33)$$

Finally, Bob makes the photons in the b6 and b9 modes pass through the PBS2. After the PBS2, the output photon state can be written as $|\Phi_9\rangle_{a1b10}$ in Equation (19), which is the maximally entangled single photon spatial state with its initial polarization feature. The whole success probability of the ECP is:

$$P = P^+ + P^- = 2|\alpha\beta|^2, \quad (34)$$

which is the same as that of the first ECP.

Interestingly, we can prove that both the concentration processes for the states in Equation (4) and Equation (5) can be repeated. Here, we also take the concentration for the state in

Equation (4) as an example. After the concentration process, we can find under the case that $t'_1 = |\alpha|^2$, the discarded items in Equation (24) which make the coherent state pick up no phase shift can be written as:

$$\begin{aligned} |\Psi_5^+\rangle_{a1b2b5b6} &= \alpha^2 |1_V, 0, 0, 1_V\rangle_{a1b2b5b6} \\ &+ \beta^2 |0, 1_V, 1_V, 0\rangle_{a1b2b5b6}. \end{aligned} \quad (35)$$

Then, with the help of the OS and the delay line, Bob makes the photons in the b5 and b6 modes pass through BS2 simultaneously, which can make:

$$|1\rangle_{b5} = \frac{1}{\sqrt{2}}(|1\rangle_{d3} - |1\rangle_{d4}), \quad |1\rangle_{b6} = \frac{1}{\sqrt{2}}(|1\rangle_{d3} + |1\rangle_{d4}). \quad (36)$$

After BS2, $|\Psi_5^+\rangle_{a1b2b5b6}$ can evolve to:

$$\begin{aligned} |\Psi_6^+\rangle_{a1b2d3d4} &= \alpha^2 |1_V, 0, 1_V, 0\rangle_{a1b2d3d4} \\ &+ \alpha^2 |1_V, 0, 0, 1_V\rangle_{a1b2d3d4} \\ &+ \beta^2 |0, 1_V, 1_V, 0\rangle_{a1b2d3d4} \\ &- \beta^2 |0, 1_V, 0, 1_V\rangle_{a1b2d3d4}. \end{aligned} \quad (37)$$

Next, the output photons in d3 and d4 modes are detected by the detectors D3 and D4, respectively. If D3 detects exactly one photon, the state in Equation (37) will collapse to:

$$|\Psi_7^+\rangle_{a1b2} = \alpha^2 |1_V, 0\rangle_{a1b2} + \beta^2 |0, 1_V\rangle_{a1b2}, \quad (38)$$

while if D4 detects exactly one photon, the state in Equation (37) will collapse to:

$$|\Psi_8^+\rangle_{a1b2} = \alpha^2 |1_V, 0\rangle_{a1b2} - \beta^2 |0, 1_V\rangle_{a1b2}, \quad (39)$$

which can be transformed to $|\Psi_7^+\rangle_{a1b2}$ by the phase-flip operation.

It can be found that $|\Psi_7^+\rangle_{a1b2}$ has the similar form with the state in Equation (4), that is to say, $|\Psi_7^+\rangle_{a1b2}$ in Equation (38) is a new less-entangled single photon state and can be reconcentrated for the next round. In the second concentration round, Bob needs to select another VBS1 with the transmission of t'_2 . The single photon source S2 emits another auxiliary photon in $|V\rangle$. By making it pass through the VBS1, the auxiliary single photon state can be described as:

$$|\psi_2'\rangle_{b5b6} = \sqrt{1-t'_2} |1_V, 0\rangle_{b5b6} + \sqrt{t'_2} |0, 1_V\rangle_{b5b6}. \quad (40)$$

According to the concentration process above, Bob makes the photons in the b2 and b5 modes pass through the QND1, and selects the items which make the coherent state pick up the phase shift of $\pm\theta$. Next, the photons in the b2 and b5 modes enter the BS1 simultaneously and the output photons in d1 and d2 modes are detected by D1 and D2, respectively. In this way, the two parties can finally obtain:

$$|\Psi_9^+\rangle_{a1b6} = \alpha^2 \sqrt{1-t'_2} |1_V, 0\rangle_{a1b6} + \beta^2 \sqrt{t'_2} |0, 1_V\rangle_{a1b6}. \quad (41)$$

Under the case that $t'_2 = \frac{|\alpha|^4}{|\alpha|^4 + |\beta|^4}$, $|\Psi_9^+\rangle_{a1b6}$ will finally be converted to the state in Equation (12). On the other hand, the discarded items in the second concentration round can be described as:

$$\begin{aligned} |\Psi_{10}^+\rangle_{a1b2b5b6} &= \alpha^4 |1_V, 0, 0, 1_V\rangle_{a1b2b5b6} \\ &+ \beta^4 |0, 1_V, 1_V, 0\rangle_{a1b2b5b6}. \end{aligned}$$

By making the photons in the b5 and b6 modes enter the BS2 simultaneously and detecting the output photons, $|\Psi_{10}^+\rangle_{a1b2b5b6}$ can finally collapse to:

$$|\Psi_{11}^+\rangle_{a1b2} = \alpha^4 |1_V, 0\rangle_{a1b2} + \beta^4 |0, 1_V\rangle_{a1b2}, \quad (42)$$

which can be reconcentrated for the third round.

In this way, we can find that by providing the auxiliary single photon and suitable VBSs with the transmittance of $t'_k = \frac{|\alpha|^{2k}}{|\alpha|^{2k} + |\beta|^{2k}}$ in each concentration round, where "k" is the iteration number, both the concentration process for the states in Equation (4) and Equation (5) can be repeated to further concentrate the discarded items.

4. DISCUSSION AND SUMMARY

In the paper, we put forward two efficient ECPs for arbitrary less-entangled single-photon spatial state. Both the two ECPs only require one pair of less-entangled single-photon spatial state and some auxiliary single photons. Moreover, they only require local operations. After the concentration process, Alice and Bob can distill the maximally spatial entangled single-photon state while preserve the polarization feature of the photon qubit. The first ECP is operated with the linear optical elements, which makes it can be realized under current experimental conditions. The second ECP is an improved ECP. We adopt the cross-Kerr nonlinearities to construct the QND, which makes this ECP can be used repeatedly to further concentrate the less-entangled state.

In both two ECPs, we need to know the exact value of the initial entanglement coefficients α and β . In the experimental process, we can obtain the values by measuring enough amount of initial less-entangled single-photon states. The VBS is the key element to perform the two protocols. Especially, in the second ECP, Bob requires to use the VBSs with different transmittance in each concentration round. The VBS is a common linear optical element in current technology. In 2012, Osorio et al. reported their results about the heralded photon amplification for quantum communication with the help of the VBS [74]. They used their setup to increase the probability η_i of the single photon $|1\rangle$ from a mixed state $\eta_i |1\rangle\langle 1| + (1 - \eta_i) |0\rangle\langle 0|$. In their experiment, they can adjust the splitting ratio of VBS from 50:50 to 90:10 to increase the visibility from $46.7 \pm 3.1\%$ to $96.3 \pm 3.8\%$. Based on their results, our requirement for the VBS can be realized in practical experiment. In the second ECP, the cross-Kerr nonlinearity is also the key element. In the practical applications, the cross-Kerr nonlinearity has been regarded as a controversial topic for a long time [92, 93]. The reason is that during the homodyne detection process, the

decoherence is inevitable, which may cause the qubit states to degrade to the mixed states [94, 95]. On the other hand, the natural cross-Kerr nonlinearity is weak so that it is difficult to determine the phase shift due to the impossible discrimination of two overlapping coherent states in homodyne detection [96]. Fortunately, according to Jeong [94], the decoherence can be extremely reduced simply by an arbitrary strong coherent state associated with a displacement $D(-\alpha)$ performed on the coherent state. Moreover, several theoretical works have proved that with the help of weak measurement, it is possible for the phase shift to reach an observable value [82–85, 97, 98].

Finally, it is interesting to calculate the success probability of the two ECPs. In both two ECPs, the single photon detection play prominent role. In practical experiment, the detection efficiency (η_p) of the single photon detector can not reach 100%. In this way, we consider the effect of η_p on the success probability of the ECPs. The total success probability of the first ECP can be written as $P = 2|\alpha\beta|^2\eta_p$. On the other hand, as the second ECP can be repeated to further concentrate the less-entangled state, the success probability in each concentration round can be calculated as:

$$\begin{aligned} P_1 &= 2|\alpha\beta|^2\eta_p, \\ P_2 &= \frac{2|\alpha\beta|^4\eta_p^2}{|\alpha|^4 + |\beta|^4}, \\ P_3 &= \frac{2|\alpha\beta|^8\eta_p^3}{(|\alpha|^4 + |\beta|^4)(|\alpha|^8 + |\beta|^8)}, \\ P_4 &= \frac{2|\alpha\beta|^{16}\eta_p^4}{(|\alpha|^4 + |\beta|^4)(|\alpha|^8 + |\beta|^8)(|\alpha|^{16} + |\beta|^{16})}, \\ &\dots\dots\dots \\ P_k &= \frac{2|\alpha\beta|^{2^k}\eta_p^{2^k}}{(|\alpha|^4 + |\beta|^4)(|\alpha|^8 + |\beta|^8)\dots(|\alpha|^{2^k} + |\beta|^{2^k})^2}, \end{aligned} \quad (43)$$

where the subscript “1”, “2”, “ \dots ”, “ k ” represent the iteration number.

In theory, the second ECP can be reused indefinitely, so that its total success probability equals to the sum of the success probability in each concentration round. The total success probability can be written as:

$$P_{total} = P_1 + P_2 + \dots + P_k + \dots = \sum_{k=1}^{\infty} P_k. \quad (44)$$

In practical experiment, the single photon detection has been a big difficulty, due to the quantum decoherence effect of the photon detector [99]. In the optical range, η_p is usually less than 30% [99, 100]. In 2008, Lita et al. reported their experimental result about the near-infrared single-photon detection. They showed the η_p at 1,556 nm can reach $95 \pm 2\%$ [101]. Based on their research results, we can make the numerical simulation on the total success probability (P_{total}) of both the two ECPs. **Figure 4** shows the P_{total} as a function of the entanglement coefficient α . In **Figure 4**, we assume $\eta_p = 90\%$. In the second ECP, we choose the repeating times $k = 1, 3, 5$ for approximation, and

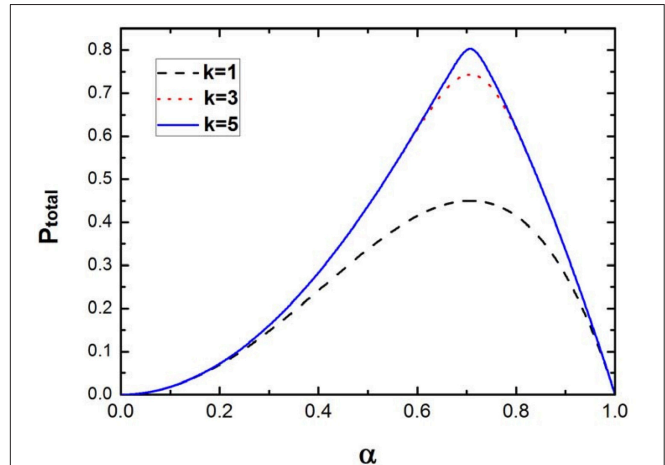


FIGURE 4 | The total success probability (P_{total}) of our second ECP altered with the initial entanglement coefficient α . As the second ECP can be repeated, we choose its iteration time $k = 1, 3, 5$ for numerical simulation. The success probability of the first ECP equals to P_{total} with $k = 1$. Considering the effect of the single photon detection efficiency (η_p) on the P_{total} , we suppose $\eta_p = 90\%$ for approximation.

the P_{total} of the first ECP equals to the case corresponding to $k = 1$. It is obvious that the P_{total} is largely dependent on the initial entanglement coefficients. The main reason is that the essence of the entanglement concentration is the entanglement transformation. The entanglement of the concentrated state comes from the initial less-entangled state. Moreover, it can be found that by repeating the second ECP, the P_{total} can be largely increased. For example, under $|\alpha| = 0.6$, we can obtain $P_{total|k=1} \approx 0.415$, $P_{total|k=3} \approx 0.615$, and $P_{total|k=5} \approx 0.619$.

In conclusion, we propose two efficient ECPs for arbitrary less-entangled single-photon entanglement state. The first ECP is operated with the linear optical elements, and the second ECP adopts the cross-Kerr nonlinearities, which makes the second ECP can be used repeatedly to further concentrate the discarded items of the first ECP. Our ECPs have some attractive advantages. First, both the two ECPs can preserve the polarization feature of the single photon qubit. So far, all the other existing ECPs for single photon state cannot achieve this goal. Second, both of them only require one pair of the less-entangled single-photon state and some auxiliary single photons. As the entanglement source is quite precious, our two ECPs are economical. Third, our two ECPs only require local operations, which can simplify the experimental operations largely. Especially, by repeating the second ECP, it can get a high success probability. Based on above properties, our two ECPs, especially the second ECP may be useful in current and future quantum communication.

AUTHOR CONTRIBUTIONS

The first author LZ proposed two efficient ECPs and wrote the main body of the manuscript. The second author D-DW participated in writing the manuscript. X-FW and S-PG made the numerical calculation of the manuscript. Y-BS supervised and revised the manuscript.

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