Constructions of secure entanglement channels assisted by quantum dots inside single-sided optical cavities

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\begin{abstract}
We propose quantum information processing schemes to generate and swap entangled states based on the interactions between flying photons and quantum dots (QDs) confined within optical cavities for quantum communication. To produce and distribute entangled states (Bell and Greenberger-Horne-Zeilinger [GHZ] states) between the photonic qubits of flying photons of consumers (Alice and Bob) and electron-spin qubits of a provider (trust center, or TC), the TC employs the interactions of the QD-cavity system, which is composed of a charged QD (negatively charged exciton) inside a single-sided cavity. Subsequently, the TC constructs an entanglement channel (Bell state and 4-qubit GHZ state) to link one consumer with another through entanglement swapping, which can be realized by exploiting a probe photon with interactions of the QD-cavity systems and single-qubit measurements without Bell state measurement, for quantum communication between consumers. Consequently, the TC, which has quantum nodes (QD-cavity systems), can accomplish constructing the entanglement channel (authenticated channel) between two separated consumers from the distributions of entangled states and entanglement swapping. Furthermore, our schemes using QD-cavity systems, which are feasible with a certain probability of success and high fidelity, can be experimentally implemented with technology currently in use.
\end{abstract}

1. Introduction

Long-distance, secure quantum communication between separated users is one of the most important issues in the quantum information processing field [1–15]. From this point of view, a flying photon is a feasible resource for transferring (and encoding) information, and for establishing a secure quantum channel (including an entanglement channel). However, this resource exponentially reduces the transmission rate, owing to optical absorption and noise in the channel, when directly transmitted for long-distance communication and secure quantum channels. In the end, this would make long-distance communication and the extended secure network impractical. Fortunately, to resolve this problem, quantum repeaters were proposed by Briegel et al. [16]. In quantum repeater schemes, through a trust center (TC), the transmission channel between separated long-distance users can be split into many short segments, which respectively share entangled states in order to link the TC and users (the construction of entanglement channels from TC to users). And then, the TC (having quantum nodes) performs entanglement swapping [16–18] to link users who want to communicate. Then, entangled states are distributed between users (constructing the entanglement channel for quantum communication) through entanglement swapping by the TC. Subsequently, for a quantum repeater, quantum information processing schemes (entanglement measurement and swapping and remote controlling qubits) using various resources were proposed, such as the single-photon and atomic systems [19–24] and the coherent state [25–28].

In quantum repeaters and quantum networks for feasible, secure, long-distance communication, quantum memory, which can implement well-isolated qubits for a sufficiently long time (reducing the decoherence effect), is also necessary during quantum information processing. Specifically, flying photons, which consumers utilize to communicate, are ideal resources owing to convenient manipulation by linear optical devices. While quantum nodes (providers) distribute the entangled states and construct the authenticated entanglement channels, TCs play a role in the quantum repeater schemes. Thus, the storage devices for preserving quantum resources over a long time are necessary on the providers’ (TCs’) side. Quantum dot (QD)-cavity systems [29–31] used for storage due to the long electron-spin coherence time ($T_2^\ast$) [32–38] within a limited spin-relaxation time ($T_1^\ast$) [39–42], are appropriate for storage of quantum information.
Moreover, the operations on a single QD spin and the preparations for the spin state have developed as described elsewhere [32,42–59]. Subsequently, many quantum information processing schemes have been proposed using the interactions between photons and the QD-cavity system, which consists of a negatively charged exciton (QD) inside a microcavity (such as quantum operation gates) [60–67], the analysis and generation of entanglement [29–31,68–71], quantum communication and networks [72–79], and the remote operations of quantum qubits [80,81].

In this paper, we propose schemes that implement the generation and distribution of entangled states (Bell and Greenberger–Horne–Zeilinger [GHZ] states) and entanglement swapping, based on QD-cavity systems using the interactions of photons and a negatively charged exciton (QD) inside a single-sided optical cavity, to construct an authenticated entanglement channel for long-distance communication. As we know, the photonic qubits of flying photons and the electron-spin qubits of excess electrons inside cavities have distinguishable advantages. The photons can be used as the best carriers for fast and reliable communication, making it easy to encode and decode information with linear optical devices. However, they are inconvenient to store for a long time (increasing decoherence). Electron-spin qubits, which can retain a long coherence time and can be readily manipulated, confined to the charged QDs inside cavities, are ideal for the storage of quantum information. Thus, those can be utilized to store and operate quantum information in quantum nodes. In our schemes, to maximize the advantages of physical resources (the flying photon and the electron on a QD), we designed our schemes to consist of users (like consumers) who are provided with an entangled state and then an entanglement channel between them from a TC (such as a channel provider). For quantum communication between consumers who want to communicate with each other, only the flying photons (entangled states and entanglement channels), which are the best carriers for communication, are distributed from TCs to consumers. To manage (provide) entangled states and an authenticated entanglement channel, the TC has quantum nodes (the QD-cavity systems) to preserve long coherence time of quantum states. Consequently, after a TC with quantum nodes (the QD-cavity systems) distributes to consumers the entangled states between the photon’s polarization and the electron’s spin, the authenticated entanglement channel between the TC’s entanglement swapping without Bell state measurement. Furthermore, our schemes via single QD coupling with a single-sided cavity (a QD-cavity system) are experimentally feasible with a certain probability of success.

2. A singly charged quantum dot in a single-sided cavity

We consider a singly charged QD, a self-assembled In(Ga)As QD, or a GaAs interface QD embedded in an optical resonant microcavity [29,30,64,71,79], which are utilized in our schemes. A micropillar cavity in Fig. 1(a) is composed of two GaAs/AlGaAs distributed Bragg reflectors (DBRs) and a transvers index guiding for three-dimensional confinement of light. The single-sided cavity is considered where one

![Diagram](https://via.placeholder.com/150)

Fig. 1. (a) A singly charged QD inside a single-sided micropillar cavity interacting with a photon, and (b) the spin selection rule for optical transitions of X− in the QD. |↑⟩ = |↑⟩ ⊗ |↑⟩ and |↓⟩ = |↑⟩ ⊗ |↓⟩ are driven by the photons |↑⟩ and |↓⟩, respectively. (c) A schematic structure of a single-sided micropillar cavity.
Fig. 2 shows the plots of the reflectances $r_ω(ω)$ from a hot cavity and $r_0(ω)$ from a cold cavity, according to the difference in coupling strengths ($g = 0.5$, $1.5x$ and $2.4x$) and side leakage rates ($κ_x = 0$, $κ_x = 1.0x$ and $κ_x = 1.5x$); $g/κ = 2.4$ and $γ/κ = 0.1g$. [44, 45, 47, 51, 56, 57]. When a negatively charged exciton $X^−$ is strongly coupled with the cavity, where $g > > (κ, γ)$ and $κ < < κ [37, 44, 51, 61, 85–88]$, we can get $|r_ω(ω)| = |r_0(ω)| = 1$, as shown in Fig. 2(a), and also $φ_ω(ω) = arg[r_ω(ω)] ≈ 0$, as shown in Fig. 2(b), with $ω_κ = ω_0$ and frequency detuning $ω−ω_κ = κ/2 < < g$. Thus, by adjusting the frequencies of the external field and cavity mode (the frequency detuning $ω−ω_κ = ± κ/2$), the reflectances $|r_ω(ω)| = |r_0(ω)| ≈ 1$ and the phase shifts $φ_ω(ω) ≈ 0$, $φ_0(ω) ≈ ± κ/2$ of the reflected photon from the cavity can be obtained for $γ/κ = 0.1$ and $ω_κ = ω_0$. If we choose the coupling strength as $g/κ = 2.4$ where $κ_x$ is negligible ($κ_x < < κ$) [29, 30, 34, 44, 51, 61, 85–88], the reflection operator $r(ˆ)$ of the reflected photon-spin state from Eq. (4) is calculated as

$$r ≈ −i[R |0⟩ ⊗ |1⟩ ⊗ |1⟩ − i[L |0⟩ ⊗ |1⟩ ⊗ |1⟩ + [R |0⟩ ⊗ |1⟩ ⊗ |1⟩ + [L |0⟩ ⊗ |1⟩ ⊗ |1⟩ |1⟩]$$

(5)

where $|r_ω(ω)| = |r_0(ω)| = 1$ and $φ_ω(ω) ≈ 0$, $φ_0(ω) ≈ − κ/2$ for $g/κ = 2.4$, $γ/κ = 0.1$, $κ_x = 0$, and $ω−ω_κ = κ/2$ with $ω_κ = ω_0$. Furthermore, the QD-cavity system (confined electron spin) should be the promising qubit system during the interaction between a photonic qubit and an electron-spin qubit. Recently, GaAs- or In(Ga)As-based charged QDs have been researched having long electron-spin coherence time ($T_2−μs$) [32–38], and long electron-spin relaxation time ($T_1−ms$) [39–42]. If the initial spin state (excess electron) is $|1⟩ + |1⟩)/√2$, then this state will be a mixed state due to spin decoherence time $τ (τ < < T_1)$, as follows:

$$ρ(τ) = \frac{1}{2} \left[ \begin{array}{cc} 1 & \exp(−τ/T_2) \\ \exp(−τ/T_2) & 1 \end{array} \right]$$

(6)

According to Eq. (6), we can get reliable quantum information processing when the interaction time between a photonic qubit and an electron-spin qubit is much shorter than electron-spin coherence time $T_2−τ (τ < < T_2)\rightarrow \exp(−τ/T_2) − 1$. Subsequently, we will utilize these interactions, Eq. (5), of the QD-cavity systems in our schemes, as explained in the next section.

3. Generation of entanglement and construction of secure entanglement channels via entanglement swapping using QD-cavity systems

When minor local communication is extended to network communication, from the users of a small group to a large number of multi-users, a fundamental requirement is efficient and secure communica-
tion. Quantum communication needs to follow this requirement. Thus, when the number of linked users grows for communication, we introduce the TC (channel provider) that can produce and distribute the entanglement channel to enhance efficiency. Also, it is possible for the TC to take charge of a trusted third party, which effectively certifies the authentication of users in the network. Therefore, researchers have proposed various protocols [3,4,7,16,72,75,76] including the TC (trusted third party, also known as “Trent”) for efficiency and security. We present four schemes for the generation of Bell and GHZ states and the construction of entanglement channels (Bell state and 4-qubit GHZ state) using the interactions between the photons and the QD-cavity systems. In our schemes, we employ a TC (provider and manager) that has the QD-cavity systems (quantum nodes) for the storage of quantum information for a long time. Flying photons, meanwhile, are used to transfer the information between consumers.

### 3.1. Generation of Bell states and construction of an entanglement channel (Bell state) via entanglement swapping using quantum nodes

![Fig. 3](Image)

**Fig. 3**. The left figure represents a theoretical schematic setup for generating and distributing a Bell state by a TC. The right setup shows that the left figure is experimentally implemented utilizing a QD-cavity system in which the TC keeps an excess electron of QD1 (the quantum node). This setup generates and distributes a Bell state (correlation of electron-spin 1 and photon A) between the TC and Alice.

We present two schemes assisted by the QD-cavity system: (1) a generation (and distribution) scheme for a Bell state between the TC and Alice, and (2) a construction scheme for an entanglement channel (linking a Bell state between Alice and Bob) via entanglement swapping by the TC, having quantum nodes and a probe photon without Bell state measurement. Fig. 3 shows a scheme to experimentally implement the theoretical description of the generated Bell state using interaction between photon A and QD1 (the TC’s quantum node). We assume that the initial state of the TC is $|\psi\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$, electron in the quantum node (QD1), and we define $|\pm\rangle = (|\uparrow\rangle \pm |\downarrow\rangle)/\sqrt{2}$ and $|\pm y\rangle = (|\uparrow\rangle \pm i|\downarrow\rangle)/\sqrt{2}$, respectively. After the interaction (by reflection operator $i\mathcal{F}$) of the reflected photon in Fig. (5) of the photon–electron in the quantum node (QD1), the initial state $|\pm\rangle_1 \otimes |\pm y\rangle_2$ is transformed to

$$|\pm\rangle_1 \otimes |\pm y\rangle_2 \xrightarrow{QD1} \frac{1}{\sqrt{2}} (|\downarrow\rangle_1 |\uparrow\rangle_2 + |\uparrow\rangle_1 |\downarrow\rangle_2 ) \equiv |\Phi^{\pm}_{\text{AB}}\rangle,$$

where $|\pm\rangle = (|\uparrow\rangle \pm |\downarrow\rangle)/\sqrt{2}$. Then, the TC sends photon A to Alice. Finally, the TC (QD1) and Alice (photon A) will share Bell state $|\Phi^{\pm}_{\text{AB}}\rangle$. In addition, all output states (four Bell states), according to the four different kinds of input state, are given in Table 1. Consequently, this scheme (Fig. 3) can generate and distribute a Bell state (according the input states) between QD1 (electron-spin 1) and photon A using the TC’s quantum node (the QD-cavity system).

<table>
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<th>Table 1</th>
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<th>The generated Bell states</th>
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Next, we propose an entanglement swapping scheme using linear optical devices and two QD-cavity systems (two quantum nodes) in the TC for constructing an entanglement channel (a Bell state) between Alice and Bob. In Fig. 4, our scheme consists of two quantum nodes (QD1 and QD2) and three flying photons (A, B, and P). The TC produces the distribution of two entangled states for TC-Alice (electron-spin 1 and photon A: a Bell state) and TC-Bob (electron-spin 2 and photon B: a Bell state), as described in Fig. 3. After the interaction between QD1 (following QD2) and probe photon P, the TC can swap to entangle photon A and photon B (constructing an entanglement channel) by single-qubit measurements on electron-spin 1, 2 (quantum nodes) and probe photon P without Bell state measurement.

Let us assume that the initial state of the TC is $|\psi\rangle^{\text{init}}_{\text{AB}} = |\mp\rangle_1 \otimes |\mp\rangle_2 \otimes |\mp\rangle_3 \otimes |\mp\rangle_4 \otimes |\mp\rangle_5 \otimes |\mp\rangle_6 \otimes |\mp\rangle_7 \otimes |\mp\rangle_8 \otimes |\mp\rangle_9 \otimes |\mp\rangle_{10}$, where subscript P means probe photon P. In the process for distribution of entangled states as described in Fig. 3, after photon A and photon B pass through S1, QD1 with the interaction of Eq. (5), and S2 (and S3, QD2 with the interaction of Eq. (5), and S4), photon-spin A-1 and A-2, $|\psi\rangle^{\text{init}}_{\text{AB}}$, are entangled, as follows:

$$|\psi\rangle^{\text{fin}}_{\text{AB}} = |\mp\rangle_1 \otimes (|\mp\rangle_2 \otimes |\mp\rangle_3 \otimes |\mp\rangle_4 \otimes |\mp\rangle_5 \otimes |\mp\rangle_6 \otimes |\mp\rangle_7 \otimes |\mp\rangle_8 \otimes |\mp\rangle_9 \otimes |\mp\rangle_{10}$|

where the interaction of the QD-cavity systems (QD1 and QD2) and photons (A and B) is expressed in Eq. (5), and the generated Bell states are listed in Table 1. Then the TC sends photons A and B to Alice and Bob, respectively, but electron-spins 1 and 2 are stored in the cavities (QD1 and QD2). Subsequently, in the process of entanglement swapping, probe photon P sequentially interacts with QD1 and QD2 according to the photon-spin interactions (in Eq. (5)) and the timetable in Fig. 4. Before single-qubit measurements on probe photon P and electron-spins 1 and 2, final state $|\psi\rangle^{\text{fin}}_{\text{AB}}$ is given by

$$|\psi\rangle^{\text{fin}}_{\text{AB}} = i\mathcal{F} (|\mp\rangle_1 \otimes |\mp\rangle_2 \otimes |\mp\rangle_3 \otimes (|\mp\rangle_4 \otimes |\mp\rangle_5 \otimes |\mp\rangle_6 \otimes |\mp\rangle_7 \otimes |\mp\rangle_8 \otimes |\mp\rangle_9 \otimes |\mp\rangle_{10}$|

where we define $|\pm\rangle = (|\uparrow\rangle \pm |\downarrow\rangle)/\sqrt{2}$, $|\mp\rangle = (|\uparrow\rangle \mp i|\downarrow\rangle)/\sqrt{2}$, and $|\mp\rangle = (|\uparrow\rangle \pm i|\downarrow\rangle)/\sqrt{2}$ conventionally. The final state $|\psi\rangle^{\text{fin}}_{\text{AB}}$ in Eq. (9) represents that two kinds of Bell state is divided into two different types of degrees of freedom (such as two
electron-spins 1 and 2 in cavities, the polarizations A and B), according to probe photon P. After probe photon P passes a polarizing beam splitter (PBS), $|\Psi^+\rangle$ is transmitted and $|\Psi^-\rangle$ is reflected, and the TC measures QD1 and QD2 on the basis of {+$\uparrow$, –$\downarrow$, –+$\uparrow$, –$\downarrow$}. All possible entanglement channels are listed in Table 2, depending on the pre-shared Bell states (TC–Alice and TC–Bob) and the TC’s measurement outcomes (photon P and electron-spins 1, 2). Consequently, this scheme (Fig. 4) can construct the entanglement channel (Bell state) between Alice and Bob for quantum communication using electron-spins 1 and 2 for quantum communication between consumers.

### Table 2

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<th>TC’s photon P</th>
<th>Two Bell states</th>
<th>TC’s measurement</th>
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<td>\Psi^+\rangle_P$</td>
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3.2. Generation of GHZ states and construction of an entanglement channel (4-qubit GHZ state) via entanglement swapping using quantum nodes

We present two schemes via QD-cavity system: (1) a generation (and distribution) scheme of a GHZ state from the TC to Alice and Bob, and (2) a construction scheme of an entanglement channel (linking a 4-qubit GHZ state between Alice and Bob) via entanglement swapping of the TC having quantum nodes and a probe photon without Bell state measurement.

We propose a scheme where the generation and distribution of a GHZ state is realized via the theoretical setup on the left side of Fig. 5 using the interactions described in Section 2 of two photons (A, B) and QD1 (electron-spin 1). If the TC prepares the initial state as $|\uparrow\downarrow\rangle_A \otimes |\uparrow\downarrow\rangle_B$ of the spin–photon system, the initial state is transformed to the final state (GHZ state) according to the interactions between the QD-cavity system (QD1) and the photons (A and B) in Eq. (5), due to the timetable in the sequence:

$$
|\uparrow\downarrow\rangle_A \otimes |\uparrow\downarrow\rangle_B \overset{QD1}{\longrightarrow} (-|--\rangle_B + |+\rangle_A + |+\rangle_B) \overset{QD2}{\longrightarrow} |\Psi\rangle_{AB},
$$

where $|\Psi\rangle = (|F\rangle \pm i|E\rangle)/\sqrt{2}$. After the interactions of the photons and the QD-cavity system, the generated GHZ states, depending on the initial states, are arranged in Table 3. Then, the TC sends photons A...
and B to Alice and Bob, respectively. Finally, our scheme (Fig. 5) can obtain all possible GHZ states between QD1 (electron-spin 1) and photons A and B by the TC’s generation and distribution using the QD-cavity system (quantum node).

The next scheme is an entanglement swapping scheme for building a secure entanglement channel (4-qubit GHZ state) between Alice and Bob using linear optical devices and the QD-cavity systems on the TC side. When quantum communications are expanded to quantum network with n parties, the entangled states, which can be used for communications and verifications of channels, should be the multipartite entanglements. Thus, many schemes for using multipartite entangled states have already been demonstrated, including quantum secret sharing [89], open-destination teleportation [90] and multiparty quantum key distribution [91,92]. In our scheme, a 4-qubit GHZ state, \( \phi^+ \equiv \frac{1}{\sqrt{3}} \sum_{\sigma} |\sigma\rangle \), can be generated from the pre-shared two GHZ states, \( \phi^+ = \frac{1}{\sqrt{3}} \sum_{\sigma} |\sigma\rangle \), by entanglement swapping without Bell state measurement. After the generation process, in which photons A, B (C, D) interact with QD1 (QD2), of entangled states according to the timetable (controlling switches) in Fig. 6, they share two GHZ states like \( \Phi_1 \otimes \Phi_2 \) (QD1-A-B and QD2-C-D), as listed in Table 3. Then the TC sends the photons to Alice (A, C) and Bob (B, D), but the two electron-spins, 1 and 2, remain on Bob’s side (quantum nodes). Subsequently, probe photon P interacts with QD1 and QD2 according to the timetable (controlling switches and the interactions of probe photon P and the two QD-cavity systems), as described in Fig. 6.

**Table 3**

All possible GHZ states can be generated by interaction between two photons and the QD-cavity system, according to the prepared states of the TC.

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<th>The prepared states of TC</th>
<th>The generated GHZ states</th>
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**Fig. 6.** The left figure represents a theoretical schematic setup of entanglement swapping by the TC for constructing an entanglement channel (4-qubit GHZ state) between Alice and Bob. The right setup shows that the left figure is experimentally implemented utilizing the QD-cavity systems in which the TC keeps excess electrons of QD1 and QD2 (two quantum nodes), and linear optical devices (delayed-loop, switches, and a PBS). The switches are controlled to transmit or reflect photons according to a timetable (black-line box). After the distributions of two GHZ states (TC–Alice–Bob), the TC constructs the entanglement channel between Alice (photons A, C) and Bob (photons B, D) for quantum communication by entanglement swapping (TC–Alice–Bob → Alice–Bob: 4-qubit GHZ state) using the interactions of probe photon P and QD1 (and QD2), and single-qubit measurements without Bell state measurement.
from Eq. (4) can be calculated as $E \equiv ( +y −y −y +y ± −y −y +y )$, $O \equiv ( +y +y +y −y ± −y −y −y )$, $E \equiv ( +y +y +y +y ± −y −y −y −y )$, and $O \equiv ( +y +y −y +y ± −y −y +y −y )$.

Where we define $\{+0\} \equiv (|↑\rangle + |↓\rangle)/\sqrt{2}$, $|+y\rangle \equiv |H\rangle$, $|-y\rangle \equiv |V\rangle$; conventionally. Also 4-qubit GHZ states of four photons are given by

$|E_{ABCD}^{1}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p+y_p+y_p) \pm 1-y_p-y_p-y_p-y_p)\rangle$,

$|E_{ABCD}^{2}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p+y_p−y_p−y_p) \pm 1-y_p+y_p+y_p+y_p)\rangle$,

$|E_{ABCD}^{3}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p −y_p −y_p +y_p) \pm 1-y_p−y_p−y_p+y_p)\rangle$,

$|E_{ABCD}^{4}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p+y_p+y_p−y_p) \pm 1-y_p+y_p+y_p−y_p)\rangle$,

$|O_{ABCD}^{1}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p−y_p+y_p+y_p) \pm 1-y_p−y_p+y_p+y_p)\rangle$,

$|O_{ABCD}^{2}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p+y_p−y_p+y_p) \pm 1-y_p+y_p−y_p+y_p)\rangle$,

$|O_{ABCD}^{3}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p−y_p−y_p+y_p) \pm 1-y_p−y_p−y_p+y_p)\rangle$,

$|O_{ABCD}^{4}\rangle \equiv \frac{1}{\sqrt{2}}(1+y_p−y_p+y_p−y_p) \pm 1-y_p+y_p−y_p+y_p)\rangle$.

And then the TC measures QD1 and QD2 on the basis of $\{|+0\rangle \equiv |H\rangle$, $|-y\rangle \equiv |V\rangle\}$. Subsequently, the authenticated entanglement channel (4-qubit GHZ state) between Alice and Bob can be constructed based on the TC’s information (the pre-shared GHZ states and the measurement outcomes: probe photon P and electron-spins 1 and 2), as listed in Table 4.

Consequently, this scheme (Fig. 6) can construct the secure entanglement channel (4-qubit GHZ state) between Alice and Bob for quantum communication through entanglement swapping using the QC-cavity systems without Bell state measurement. Thus, our scheme has the same advantages, which are the enhancement of implementation and efficiency with no Bell state measurement and the authentication channel by the TC’s management (approval) of the channel, as the generation scheme of an entanglement channel (Bell state) in Fig. 4.

4. Discussion and conclusion

In our schemes, the most important component is the QC-cavity system, which can implement the interactions between photons (flying: TC → consumers) and the located electrons (stored in the TC’s quantum nodes) of the QDs inside microcavities. Thus, it is necessary for our reliable schemes to analyze the efficiency of output (photon-spin state) from the QC-cavity system, and the implementation of a charged QD (negatively charged exciton) inside a single-sided cavity for the probability of success of the quantum nodes.

For the efficiency of the quantum node (the QC-cavity system), if we can take the experimental parameters (applied to our schemes) of Eq. (5) ($\alpha = 2.4$, $r/k = 0.1$, $\kappa = 0$, and $\omega = \omega_c = \omega_i$) [29,30,37,44,51,61,65–88], as described in Section 2, then the reflectances and phase shifts are $\rho_{P}(\omega) \approx 0$, $\phi_{P}(\omega) \approx -\pi/2$ and $\rho_{e}(\omega) = \rho_{e}(\omega) \approx 1$ under ideal conditions after the instructions of the QC-cavity system. Then, the fidelity (F) between the ideal state $|\psi_{e}\rangle$ (from Eq. (5)) and the practical state $|\psi_{pr}\rangle$ (from Eq. (4)) can be calculated as

$$F = \left| \frac{\langle \psi_{e} | \psi_{pr} \rangle}{\langle \psi_{pr} | \psi_{pr} \rangle} \right| = \left| \frac{1 + \frac{i}{\sqrt{2}} \epsilon + \frac{1}{\sqrt{2}} \epsilon \phi_{P}(\omega) = \phi_{P}(\omega)}{\sqrt{1 + \frac{i}{\sqrt{2}} \epsilon + \frac{1}{\sqrt{2}} \epsilon \phi_{P}(\omega) \phi_{P}(\omega)}} \right| \left| \frac{1 + \frac{i}{\sqrt{2}} \epsilon + \frac{1}{\sqrt{2}} \epsilon \phi_{P}(\omega) \phi_{P}(\omega)}{\sqrt{1 + \frac{i}{\sqrt{2}} \epsilon + \frac{1}{\sqrt{2}} \epsilon \phi_{P}(\omega) \phi_{P}(\omega)}} \right|$$

where the input state is $(|↑\rangle + |↓\rangle)/\sqrt{2}$ and $|\psi_{e}\rangle$ is $|\psi_{pr}\rangle$. Fig. 7 shows

Table 4

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<th>Two Bell states</th>
<th>TC’s measurement of QD1 and QD2</th>
<th>Two Bell states</th>
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the fidelity according to the differences in practical parameters: (a) $g/\kappa$ and (b) $\kappa/g$, for fixed $\omega - \omega_0 = \kappa/2$, $\gamma/\kappa = 0.1$, and $\omega - \omega_0 = \omega_1$. As shown in Fig. 7, the fidelity of the output state from the QD-cavity system approaches 1 when $g/\kappa$ is the strong coupling strength ($g > (\kappa, \gamma)$) and $\kappa/g$ is the small side leakage rate ($\kappa > g$). According to the above analysis, various experimental methods have been researched to achieve strong coupling between the QD and the cavity for quantum information processing with high fidelity and efficiency. For micropillars with diameter $d = 1.5 \mu m$, a decay rate of $X^-$ obtains $\gamma/2 \approx 1 \mu eV$ when temperature $T \approx 2 K$ [85]. The coupling strength in a micropillar cavity of $d = 1.5 \mu m$ can achieve $g/\kappa + \kappa/\gamma \approx 0.5$ for quality factor $Q \approx 8800$ [44], and can increase to $g/\kappa + \kappa/\gamma \approx 2.4$ for quality factor $Q \approx 40000$ [86]. Also, $g \approx 80 \mu eV$ and quality factor $Q \approx 40000$ (including the side leakage rate $g$) have been implemented with In$_{0.5}$Ga$_{0.5}$As, and a rather small $\kappa$ can be obtained by optimizing the etching process [51]. Meanwhile, coupling strength $g$ depends on QD exciton oscillator strength and mode volume $V$: $\kappa$ is determined by the cavity quality factor, and coupling strength $g$ and $\kappa$ can be controlled independently to achieve a larger $g/(\kappa + \kappa)$. Loo et al. [87] achieved $g \approx 16 \mu eV$ and $\kappa \approx 20.5 \mu eV$ with $Q \approx 65000$ when $d = 7.3 \mu m$ of a micropillar. And the quality factor improved to $Q \approx 215000(\approx 6.2 \mu eV)$ with a lower side leakage rate [88]. Furthermore, for reliable interactions (photon–electron) of the QD-cavity system and suitable storage of quantum information in our schemes, the requirements of the QDs are a long electron-spin coherence time ($T_1^e$), long electron-spin relaxation time ($T_1^e$), and techniques for manipulation and preparation of the single electron-spin. A lot of research has been conducted into extending electron-spin coherence time $T_1^e$ to $2.6 \mu s$ [32–38]. For GaAs-based or InAs-based charged QDs, recent experiments have shown long electron-spin coherence time ($\mu s$) after suppressing the nuclear spin fluctuations [32,33,35] or by using spin echo techniques [33,34,36–38]. Due to the suppressed photon-electron in the QDs, a long electron-spin relaxation time, $T_1^e$, has been acquired [39]. For high fidelity in the interactions of the QD-cavity system (to reduce spin decoherence time $t$), electron-spin relaxation time $T_1^e$ is predicted to be 20ns in a magnetic field [40], and can be much longer for a lower magnetic field [41,42]. The operations (manipulations) on a single QD spin for our schemes can be achieved by using pulsed magnetic resonance techniques, nanosecond microwave pulses, or picosecond/femtosecond optical pulses [43,46,49,52], as well as by using a microwave or optical pulse [54,55]. The single QD spin manipulation for the preparations was experimentally performed by optical pumping or optical cooling [48,50]. The spin superposition state of an excess electron can be generated by performing single-spin rotations using nanosecond electron spin resonance microwave pulses [32,42]. Finally, the above experimental research indicated that a charged QD (negatively charged exciton) inside a single-sided cavity (quantum node) is one of the promising resources in our schemes for generating the entanglement channel using quantum nodes. Consequently, we can get experimentally feasible schemes (construction entanglement channels: Bell state and 4-qubit GHZ state) with a certain probability of success by employing QD-cavity systems. Furthermore, our schemes, which are presented in Section 2, have advantages besides feasible implementation, as follows:

(1) For the generation of entangled states and distribution of entanglement channels, we can obtain a certain probability of success and high fidelity if we take the experimental conditions (strong coupling strength and low side leakage rate: $g > (\kappa, \gamma)$ and $\kappa < g$), as described in Section 2 and Fig. 7, using the QD-cavity system with current technology. Thus, compared with the probabilistic schemes [93,94] which can operate and teleport using linear optical elements to remotely manipulate the photonic qubits, our schemes can acquire the deterministic operations.

(2) We designed our schemes to maximize the merits of physical resources (flying photons and electron-spin inside a cavity). The photons are the best carriers to encode and decode information with linear optical devices, for fast and reliable communication. However, it is inconvenient for them to store for a long time due to increasing decoherence effect. Electron-spin qubits confined to the charged QDs inside cavities can obtain a long coherence time for the storage of quantum information due to the long electron-spin coherence time ($T_1^e$) within a limited spin-relaxation time ($T_1^e/\mu s$) [32–38] within a limited spin-relaxation time ($T_1^e/\mu s$) [39–42]. Our scheme, based on the advantages of physical resources, is composed of the TC (quantum nodes: generation and distribution of entangled states and the construction of an entanglement channel with the long storage time) and the consumers (Alice and Bob: fast and reliable communication with easy manipulation) having distributed photons.

(3) The proposed schemes (via entanglement swapping) for construct-
ing a channel based on QD-cavity systems can be operated to construct entanglement channels between consumers using single-qubit measurements and a probe photon without Bell state measurement. Thus, we can enhance the feasibility to realize entanglement swapping with no Bell state measurement (having difficulty with the implementation).

(4) Before quantum communication by consumers, the TC plays the roles of provider and manager of the channel. This means that only authenticated consumers can use the entanglement channel to communicate after the verification process of the TC (the initial state and measurement outcomes). Specifically, our schemes guarantee the secure channel for quantum communication by the TC (having quantum nodes).

Consequently, we demonstrated that our schemes have the advantage of experimentally feasible realization using QD-cavity systems, and efficiency and security in terms of quantum communication with no Bell state measurement and the existence of the TC (constructing entanglement channels).

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