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

Jino Heo[a], Min-Sung Kang[b], Chang-Ho Hong[c], Seong-Gon Choi[a], Jong-Phil Hong[a,*]

[a] College of Electrical and Computer Engineering, Chungbuk National University, Chungdae-ro 1, Seowon-Gu, Cheongju, Republic of Korea
[b] Center for Quantum Information, Korea Institute of Science and Technology (KIST), Seoul 136-791, Republic of Korea
[c] National Security Research Institute, P.O. Box 1, Yuseong, Daejeon 34188, Republic of Korea

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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 to exploit 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.

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^e~μs) [32–38] within a limited spin-relaxation time (T_1^e~ms) [39–42], are appropriate for storage of quantum information.

* Corresponding author.
E-mail address: jongph@cbnu.ac.kr (J.-P. Hong).

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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 is constructed by 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/Al(Ga)As distributed Bragg reflectors (DBRs) and a transvers index guiding for three-dimensional confinement of light. The single-sided cavity is considered where one

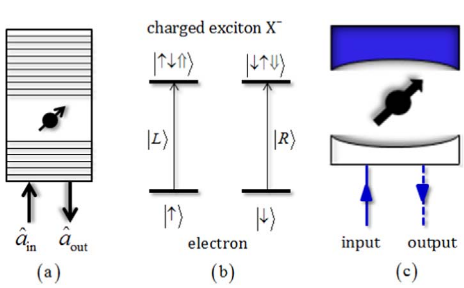

Fig. 1. (a) A singly charged QD inside a single-sided micropillar cavity interacting with a photon, and (b) the spin selection rule for optical transitions of X^- in the QD. $|\uparrow\rangle \to |\uparrow\downarrow\Uparrow\rangle$ and $|\downarrow\rangle \to |\downarrow\uparrow\Downarrow\rangle$ are driven by the photons $|L\rangle$ and $|R\rangle$, respectively. (c) A schematic structure of a single-sided micropillar cavity.

(bottom) DBR is partially reflective of the light into and out of the cavity, while another (top) DBR is 100% reflective. The QD is located in the center of the cavity for maximal light–matter coupling. $\hat a_{\text{in}}$ and $\hat a_{\text{out}}$ are the input and output field operators. Fig. 1(b) shows the spin selection rule for spin-dependent optical transitions [82] of a negatively charged exciton (X^-) in a QD due to the Pauli exclusion principle. When an excess electron is injected into the QD (singly charged) [29,30,64,71,79], optical excitation can create X^- (consisting of two electrons bound to one hole [83]). If the spin state of the excess electron is in the state $|\uparrow\rangle \equiv |+1/2\rangle$ ($|\downarrow\rangle \equiv |-1/2\rangle$), the left-circularly polarized $|L\rangle$ (the right-circularly polarized $|R\rangle$) photon can be resonantly absorbed to create the state $|\uparrow\downarrow\Uparrow\rangle$ ($|\downarrow\uparrow\Uparrow\rangle$) of X^- where $|\Uparrow\rangle$ and $|\Downarrow\rangle$ ($J_z = +3/2$ and $-3/2$) represent heavy-hole spin states.

The above process for the interaction between a photon and a QD-cavity system means that the circularly polarized photon directed into the QD-cavity system can be coupled with the electron spin and feels a hot cavity ($|L\rangle, |\uparrow\rangle$ or $|R\rangle, |\downarrow\rangle$), or can be decoupled and feels a cold cavity ($|R\rangle, |\uparrow\rangle$ or $|L\rangle, |\downarrow\rangle$) when the dipole selection rule is fulfilled. Due to this spin selection rule, the coupled photon (feeling a hot cavity) and the uncoupled photon (feeling a cold cavity) acquire different phases and amplitudes after they are reflected from the cavity. The reflection coefficient of this QD-cavity system can be attained by solving the Heisenberg equation of motion for the cavity mode operator ($\hat a$) and the dipole operator ($\hat\sigma_-$) of X^- with the input–output relation [84]:

$$\frac{d\hat a}{dt} = -\left[i(\omega_c-\omega)+\frac{\kappa}{2}+\frac{\kappa_s}{2}\right]\hat a - g\hat\sigma_- - \sqrt{\kappa}\,\hat a_{\text{in}},$$
$$\frac{d\hat\sigma_-}{dt} = -\left[i(\omega_{X^-}-\omega)+\frac{\gamma}{2}\right]\hat\sigma_- - g\hat\sigma_Z\hat a,$$
$$\hat a_{out} = \hat a_{in} + \sqrt{\kappa}\,\hat a, \qquad (1)$$

where ω, ω_c, and ω_{X^-}, respectively, are the frequencies of the external field, the cavity mode, and the dipole transition of X^-; g is the coupling strength between X^- and the cavity mode; and $\kappa/2$, $\kappa_s/2$, and $\gamma/2$ are the decay rate, the side leakage rate of the cavity mode, and the decay rate of X^-, respectively. If X^- stays in the ground state, we can take $\langle\hat\sigma_Z\rangle \approx -1$ and $\hat\sigma_Z\hat a = -\hat a$. In the steady state, the reflection coefficient for the QD-cavity system is given by

$$\frac{\hat a_{\text{out}}}{\hat a_{\text{in}}} = r(\omega) \equiv |r(\omega)|e^{i\varphi(\omega)}$$
$$= \frac{[i(\omega_{X^-}-\omega)+\gamma/2][i(\omega_c-\omega)-\kappa/2+\kappa_s/2]+g^2}{[i(\omega_{X^-}-\omega)+\gamma/2][i(\omega_c-\omega)+\kappa/2+\kappa_s/2]+g^2}, \qquad (2)$$

where $|r(\omega)|$ is the reflectance and $\varphi(\omega) = \arg[r(\omega)]$ is the phase shift. Subsequently, the reflection coefficients [$r_h(\omega)$: hotcavity] and [$r_0(\omega)$: coldcavity] from Eq. (2) are given by

$$r(\omega) = r_h(\omega) \equiv |r_h(\omega)|e^{i\varphi_h(\omega)}$$
$$= \frac{[i(\omega_{X^-}-\omega)+\gamma/2][i(\omega_c-\omega)-\kappa/2+\kappa_s/2]+g^2}{[i(\omega_{X^-}-\omega)+\gamma/2][i(\omega_c-\omega)+\kappa/2+\kappa_s/2]+g^2},$$
$$r_0(\omega) \equiv |r_0(\omega)|e^{i\varphi_0(\omega)} = \frac{i(\omega_c-\omega)-\kappa/2+\kappa_s/2}{i(\omega_c-\omega)+\kappa/2+\kappa_s/2}, \qquad (3)$$

where $g \neq 0$ (hot cavity) due to the coupled QD and cavity, $r_h(\omega) = r(\omega)$, and $g = 0$ (cold cavity) due to the uncoupled QD and cavity. Thus, after reflection from the QD-cavity system, we can get reflection operator $\hat r(\omega)$ of the state (photon-spin), as follows:

$$\hat r(\omega) = |r_0(\omega)|e^{i\varphi_0(\omega)}(|R\rangle\langle R|\otimes|\uparrow\rangle\langle\uparrow| + |L\rangle\langle L|\otimes|\downarrow\rangle\langle\downarrow|)$$
$$+|r_h(\omega)|e^{i\varphi_h(\omega)}(|R\rangle\langle R|\otimes|\downarrow\rangle\langle\downarrow| + |L\rangle\langle L|\otimes|\uparrow\rangle\langle\uparrow|). \qquad (4)$$

According to the parameters of the QD-cavity system, the significant differences from reflectance and phase shift in reflection coefficient $r(\omega)$, manifested between the hot and cold cavities, which comply with the spin selection rule, can be exploited to perform the quantum information processing schemes [29–31,60–81].