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Scheme for swapping two unknown states of a photonic qubit and an electron-spin qubit using simultaneous quantum transmission and teleportation via quantum dots inside single-sided optical cavities

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A B S T R A C T

We propose a scheme for swapping two unknown states of a photon and electron spin confined to a charged quantum dot (QD) between two users by transferring a single photon. This scheme simultaneously transfers and teleports an unknown state (electron spin) between two users. For this bidirectional quantum communication, we utilize the interactions between a photonic and an electron-spin qubits of a QD located inside a single-sided optical cavity. Thus, our proposal using QD-cavity systems can obtain a certain success probability with high fidelity. Furthermore, compared to a previous scheme using cross-Kerr nonlinearities and homodyne detections, our scheme (using QD-cavity systems) can improve the feasibility under the decoherence effect in practice.

1. Introduction

Quantum optics plays a significant role in experimentally realizing quantum information processing, such as quantum communication [1–6], quantum networks [7,8], quantum computing [9–11], quantum operational gates [12–14], and quantum entanglement [15–17].

The cross-Kerr nonlinearity (XKNL) effect is a good resource for realizing quantum information processing schemes. In principle, because the XKNL effect can induce photon interactions, it can implement photonic multi-qubit gates, which can be utilized to handle quantum information [12–14]. For efficiency and feasibility in experimental implementation of the quantum information process, various methods have been studied, such as measurement strategies (homodyne detections [3–6,12,13,16] and photon-number measurement [9,11,15,19,21,22]) and structures of multi-qubit gates (quantum bus beams [9,22] and the coherent superposition state [4,23]). However, the experimental realization of strong XKNL is still a big challenge [24]. Furthermore, the decoherence effect, which gives rise to evolution of the state of photons into a mixed state after homodyne measurement (by loss of photons and dephasing), is also unavoidable when a coherent state is transmitted through a fiber in practice [11,15,18–21]. As a result, the fidelity of optical multi-qubit gates will decrease for quantum information processing.

From this point of view, well-isolated qubits might not necessarily suffer from the same decoherence effects in Kerr medium. The quantum dot (QD)-cavity system [25–27], which is one of the candidates for quantum information processing, has recently attracted extensive attention. As we know, photons are ideal resources for transferring quantum information in fast and reliable long-distance communication and for readily manipulating linear optical devices. On the other hand, QDs are suitable for the storage of quantum information in solid-state quantum systems, and can acquire a long coherence time (extending to μs) [28–30]. Moreover, the manipulations of QDs have developed as described in [31–33]. Therefore, various photon–photon, electron–photon, and electron–electron quantum information processing schemes have been proposed using a single QD coupling to a microcavity (QD-cavity system), such as quantum communication and networks [34–41], quantum operational gates [27,42–45], and the measurement and generation of entanglement [25,26,46,47].

In this paper, we propose a deterministic simultaneous quantum transmission and teleportation (SQTTP) scheme for exchanging two unknown states between two users (Alice and Bob) by transmitting only one photon, which is Alice's unknown state, and the probe photon via linear optical devices and three QD-cavity systems. To obtain controlled operations (realized by multi-qubit

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gates) for this bidirectional communication scheme, we exploit the interaction between the photon and a single electron spin in a single QD inside a microcavity [25–27]. This interaction generates different phase shifts according to the polarization (right-circular and left-circular) of the reflected photons from the QD-cavity system induced by a single electron spin confined to a charged QD (negatively charged exciton) with spin-dependent optical transitions strongly coupled to a microcavity.

In the existing SQTTP scheme, Heo et al. [4] utilized the weak XKNLs, coherent superposition states (probe beams) and P-homodyne detections for bidirectional communication. However, this scheme [4] has some difficulties for experimental implementation in a laboratory, as follows. First, it is experimentally difficult to make the large-magnitude phase shift induced by XKNL [24]. In addition, Kok [48] showed that it is generally not possible to change the sign of the conditional phase shift ($-\theta$). Second, the pure quantum state evolving into a mixed state (dephasing the coherent parameters) induced by the decoherence effect is inevitable in the existing SQTTP scheme [4] by using the coherent superposition state and P-homodyne. Fortunately, realization of the strong coupled QD-cavity system has been demonstrated in microcavities and nanocavities [49–53] for quantum information processing. And then, various quantum communication and network schemes [34–41] based on the QD-cavity system have been proposed to achieve a nontrivial nonlinearity between two individual qubits. Consequently, we demonstrate how to enhance the experimental feasibility of the SQTTP scheme by using QD-cavity systems, compared with Heo et al.'s scheme [4], which employed XKNLs and P-homodyne detections and was vulnerable to the decoherence effect.

2. A singly charged quantum dot inside single-sided optical cavity

We introduce a singly charged QD [25–27], which is a self-assembled In(Ga)As QD or a GaAs interface QD embedded in an optical resonant microcavity, utilized in our SQTTP scheme. A micropillar cavity in Fig. 1(a) is composed of two GaAs/Al(Ga)As distributed Bragg reflectors (DBRs) and a transverse index guiding for three-dimensional confinement of light. We consider that one (bottom) DBR is partially reflective of the light into and out of the cavity, while another (top) DBR is 100% reflective, the single-sided cavity, and the QD is located in the center of the cavity for maximal light-matter coupling [25–27]. $\hat{a}_{\text{in}}$ 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 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) [25–27], optical excitation can create X^- (consisting of two electrons bound to one hole [54]). 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 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 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 field operator ($\hat{a}$) and the dipole operator ($\hat{\sigma}_-$) of X^- with the input–output relation [55]:

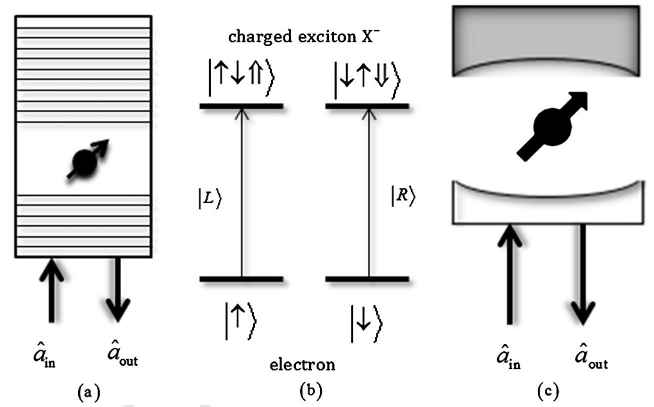

Fig. 1. (a) A singly charged QD inside a single-sided micropillar cavity interacting with a photon. (b) Spin selection rule for optical transitions of X^- in the QD. $|\uparrow\rangle \to |\uparrow\downarrow\Uparrow\rangle$ and $|\downarrow\rangle \to |\downarrow\uparrow\Downarrow\rangle$ are driven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

$$\frac{d\hat{a}}{dt} = -\left[i(\omega_c - \omega) + \frac{\kappa}{2} + \frac{\kappa_s}{2}\right]\hat{a} - g\hat{\sigma}_- - \sqrt{\kappa}\hat{a}_{\text{in}},$$
$$\frac{d\hat{\sigma}_-}{dt} = -\left[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}\right]\hat{\sigma}_- - g\hat{\sigma}_Z\hat{a}, \quad \hat{a}_{\text{out}} = \hat{a}_{\text{in}} + \sqrt{\kappa}\hat{a}, \tag{1}$$

where ω, ω_c, and ω_{X^-}, respectively, are the frequencies of the external field, cavity mode, and the dipole transition of X^-; g is the coupling strength between X^- and the cavity mode; $\kappa/2$, $\kappa_s/2$, and $\gamma/2$ are the decay rate, the side leakage rate of the cavity mode, and the decay rate of X^-, respectively. In the approximation of weak excitation where the charged QD is predominantly in the ground state, $\langle\hat{\sigma}_Z\rangle \approx -1$. In the steady state, the reflection coefficient for the QD-cavity system is given by

$$\frac{\hat{a}_{\text{out}}}{\hat{a}_{\text{in}}} = r(\omega) \equiv |r(\omega)|e^{i\varphi(\omega)}$$
$$= 1 - \frac{\kappa[i(\omega_{X^-} - \omega) + \gamma/2]}{[i(\omega_{X^-} - \omega) + \gamma/2][i(\omega_c - \omega) + \kappa/2 + \kappa_s/2] + g^2}, \tag{2}$$

where $|r(\omega)|$ is the reflectance, and $\varphi(\omega) = \arg[r(\omega)]$ is the phase shift. For the requirement of the weak-excitation approximation, let us consider that the intracavity photon number should be less than the critical photon number $n_0 = \gamma^2/2g^2$ (the number of photons in the cavity required to saturate the QD response [46,56], and also the spectral width of single photons should be much smaller than the linewidth of the cavity mode for remaining the charged QD in the ground state. The spin selection rule is not perfect for a realistic QD due to the heavy-light hole mixing. This can reduce the fidelity of the QD-cavity system by the hole mixing in the valence band. Fortunately, the hole mixing could be reduced by engineering the shape and size of QDs or choosing different types of QDs.

Let us assume the resonant interaction with $\omega_{X^-} = \omega_c$ [25–27, 49,50] instead of the dispersive interaction, when the spin state of the excess electron is in the state $|\uparrow\rangle$($|\downarrow\rangle$), the state $|R\rangle$($|L\rangle$) of a photon feels a cold cavity (the QD is uncoupled to the cavity). While the state $|L\rangle$($|R\rangle$) of a photon feels a hot cavity (the QD is coupled to the cavity). For the cold cavity, we can obtain reflection coefficient $r_0(\omega)$ from Eq. (2), as follows:

$$r_0(\omega) \equiv |r_0(\omega)|e^{i\varphi_0(\omega)} = \frac{i(\omega_c - \omega) - \kappa/2 + \kappa_s/2}{i(\omega_c - \omega) + \kappa/2 + \kappa_s/2}, \tag{3}$$

where $g = 0$ (cold cavity) due to the uncoupled QD with cavity. When κ_s is negligible, as described elsewhere [25–27,49,50], we

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