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Design of a spin-coherent photo detector for high-fidelity and high-yield photon-spin quantum state transfer

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We analyzed the yield and fidelity of the quantum state transfer (QST) from a photon polarization qubit to an electron spin qubit in a spin-coherent photo detector consisting of a semiconductor quantum dot and a photonic cavity. We determined the optimal conditions that allow the realization of both high-yield and high-fidelity QST.

A quantum repeater is a promising technology [1–3] which makes it possible to drastically expand the distance of quantum key distribution as well as to realize scalable quantum networks. The quantum repeater requires not only messenger qubits but also processing qubits. A photon is the most convenient candidate for the messenger qubit, and an electron spin in a semiconductor quantum dot is one of the most convenient candidates for processing qubits. Therefore it is important to investigate the possibility of a photon-spin quantum state transfer (QST) [4–6], which would transfer quantum information from a photon-polarization (photon qubit) to an electron-spin (spin qubit), as an interface device for quantum repeaters. Such a photon-spin QST can be performed using a semiconductor spin-coherent photo detector, as proposed by Vrijen and Yablonovitch [4], who showed that the well-known optical orientation in a semiconductor heterostructure can be used for QST. The photo detector has a quantum dot whose energy levels are shown in Fig. 1(a). By applying a magnetic field, we can arrange the light-hole state $|lh+\rangle = |3/2, 1/3\rangle + |3/2, -1/2\rangle$ to the topmost level of the valence band. One can excite the electron with the spin state state $\alpha_+ |\uparrow\rangle + \alpha_- |\downarrow\rangle$ from the light-hole state $|lh+\rangle$ by the input photon with the polarization state $\alpha_+ |\sigma^+\rangle + \alpha_- |\sigma^-\rangle$.

In order to realize the quantum repeater, high-yield and high-fidelity QST is desired. Therefore we have to analyze the QST process, and find the optimal device conditions for high-yield and high-fidelity QST. We examined the model shown in Fig. 1(b) as the spin-coherent photo detector. The quantum dot is located in the photonic cavity and is also connected to the continuum of the hole through the tunneling barrier in order to extract the created hole. The input photon propagates the x-axis and enters the cavity (one-sided cavity)[7, 8]. The coupling between the input photon and the cavity photon is represented by the cavity damping rate κ. The cavity photon excites the electron-hole pair or exciton in the dot. The coupling constant between the cavity photon and the dot exciton is g. Due to the selection rule shown in Fig. 1(a), the electron spin state is determined by the input photon polarization state. Once the electron-hole pair is excited in the quantum dot, the created hole is extracted to the continuum with the extraction rate γ_h,

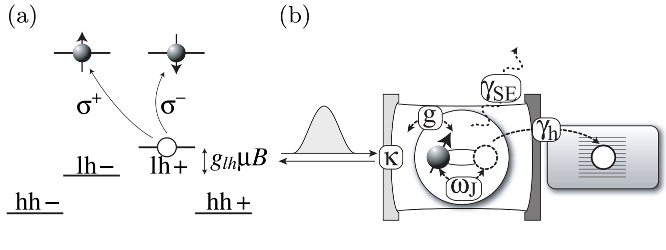

FIG. 1: (a) Energy levels of the quantum dot. From the $|lh+\rangle$ state, an electron with the $|\uparrow\rangle$ ($|\downarrow\rangle$) spin state is optically excited by the right-handed (left-handed) circularly polarized photon $|\sigma^+\rangle$ ($|\sigma^-\rangle$) (b) The theoretical model considered. The model includes the input/output photon field, the cavity, and the quantum dot where the QST is carried out. The continuum of the hole state is attached to the quantum dot via a tunneling barrier.

and the electron spin is left in the dot. The QST process is then completed. In addition to the above processes, we also considered the electron-hole exchange interaction ω_J and the spontaneous emission rate of the dot exciton γ_{SE}. The electron-hole exchange interaction modifies the orientation of the electron-spin, while the hole is in the dot and therefore reduces the fidelity. Spontaneous emission leads to a decrease in yield.

The state vector of the system under consideration is expressed as

$$
\begin{aligned}
|\Psi(t)\rangle = &\sum_{\sigma=\pm} \int dx \phi_\sigma^{\mathrm{ph}}(x;t) |x,\sigma\rangle + \sum_{\sigma=\pm} \phi_\sigma^{\mathrm{cav}}(t) |\mathrm{cav},\sigma\rangle \\
&+ \sum_{s=\uparrow\downarrow} \varphi_s^{\mathrm{ex}}(t) |\mathrm{ex}, s\rangle + \sum_{\mu} \phi_\mu^{\mathrm{noncav}}(t) |\mu\rangle \\
&+ \sum_{s=\uparrow\downarrow} \sum_{l} \varphi_{ls}^{\mathrm{spin}}(t) |l, s\rangle , \qquad (1)
\end{aligned}
$$

where $|x,\sigma\rangle$ denotes the input/output photon state at position x and polarization $\sigma = \sigma^\pm$; $|\mathrm{cav},\sigma\rangle$ the cavity photon with polarization σ; $|\mathrm{ex}, s\rangle$ the exciton state in the dot with electron spin state $s = \uparrow, \downarrow$; $|\mu\rangle$ the external noncavity photon (μ represents the wave number and corresponding polarization); and $|l, s\rangle$ the state in which the electron with spin state s is in the dot and the hole is

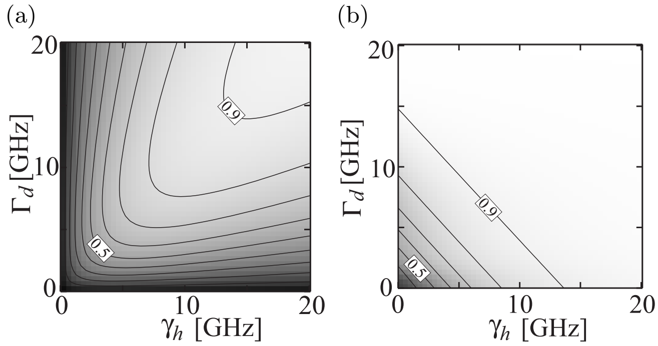

FIG. 2: Contour plots of (a) yield and (b) fidelity, as functions of the extraction rate of hole γ_h and the effective dipole relaxation rate Γ_d.

in the continuum state l. Here $\phi^{\rm ph}_\sigma(x;t)$, $\phi^{\rm cav}_\sigma(t)$, $\varphi^{\rm ex}_s(t)$, $\varphi^{\rm spin}_{ls}(t)$, and $\phi^{\rm noncav}_\mu(t)$ are coefficients to be determined by solving the Schrödinger equation. For later use, we name the state represented by the last term in Eq. (1) the "spin state".

In order to analyze the QST process in this model, we must consider the scattering problem from the initial input photon state to the final spin state. The initial state at $t = 0$ is written as

$$|\Psi(0)\rangle = \int dx \phi^{\rm ph}(x;t=0) \sum_{\sigma=\sigma^\pm} \alpha_\sigma |x,\sigma\rangle , \qquad (2)$$

where α_+ and α_- are the probability amplitudes which characterize the superposition state of the photon qubit $\alpha_+ |\sigma_+\rangle + \alpha_- |\sigma_-\rangle$. The coefficient $\phi^{\rm ph}(x;t=0)$ represents the input photon wave packet. We consider a Gaussian wave packet with the center frequency $\omega_{\rm ph}$ and the bandwidth $\Delta\omega_{\rm ph}$. By applying the the Schrödinger equation, we can obtain the final state of the system for $t \to \infty$. The final spin state is characterized by the reduced density matrix $\rho^{\rm spin}$ defined as $\rho^{\rm spin}_{ss'} = \sum_l \varphi^{\rm spin}_{ls}(\infty)\varphi^{\rm spin}_{ls'}(\infty)^*$ for $s,s' = \uparrow,\downarrow$. The efficiency of the QST is represented by the yield defined as $P = \rho^{\rm spin}_{\uparrow\uparrow} + \rho^{\rm spin}_{\downarrow\downarrow}$, which represents the probability that the electron spin is left in the dot at the final state. Using $\rho_{\rm spin}$, we can define the fidelity of the QST as $F = \langle\Psi_I| \rho^{\rm spin} |\Psi_I\rangle /P$, where $|\Psi_I\rangle = \alpha_+ |\uparrow\rangle + \alpha_- |\downarrow\rangle$ is the ideal spin state.

For high-yield QST, the strong cavity damping condition $\kappa \gg \Delta\omega_{\rm ph}$ should be satisfied so that the input photon can effectively enter the cavity. In what follows we take $\kappa = 15$GHz and $\Delta\omega_{\rm ph} = 5$GHz. We also assume $\omega_J = 5$GHz and $\gamma_{\rm SE} = 1$GHz. Figure 2(a) shows the contour plot of the yield as a function of Γ_d and γ_h, where $\Gamma_d \equiv |g|^2/\kappa$ is the effective dipole relaxation rate, which represents the enhanced spontaneous emission rate of the exciton due to the coupling with the cavity photon. To consider in detail the effects of γ_h on the yield, let us fix Γ_d at a certain value and increase γ_h from zero. As γ_h increases, the recombination of the dot exciton is suppressed, hence the yield increases with increasing γ_h. However, the increase of γ_h prevents the creation of the dot exciton, which suppresses the yield for large values of γ_h. Therefore, the yield takes its maximum value at $\gamma_h \sim \Gamma_d$. The condition $\Delta\omega_{\rm ph} \ll \Gamma_d, \gamma_h$ is also important for producing a high yield in order to transfer the energy effectively from the input photon to the exciton. The condition for this high yield is summarized as $\Delta\omega_{\rm ph} \ll \gamma_h \sim \Gamma_d$.

Fig. 2(b) is the contour plot of the fidelity. Note that the fidelity is reduced from unity for $\Gamma_d + \gamma_h < \omega_J$. The lifetime of the exciton state $\varphi^{\rm ex}_s(t)$ is given as $(\Gamma_d + \gamma_h)^{-1}$ for the impulse-like input photon wave packet in the case of strong cavity damping. In order to avoid the effects of the electron-hole exchange interaction, the lifetime of the exciton state should be much shorter than the characteristic time of the exchange interaction ω_J^{-1}. Therefore, the condition $\omega_J \ll \Gamma_d + \gamma_h$ is required for a high-fidelity QST.

In conclusion, we have analyzed the yield and fidelity of the QST in a spin-coherent semiconductor photo detector. By considering a model in which the quantum dot is coupled with the photonic cavity, we determined the optimal conditions for high-yield and high-fidelity QST. Briefly, the strong cavity damping condition; $\Delta\omega_{\rm ph} \ll \kappa$, and the matching condition; $\omega_{\rm ph} \ll \gamma_h \sim \Gamma_d$, should be satisfied in order to obtain high yield. For high-fidelity QST, a small electron-hole exchange interaction as $\omega_J \ll \Gamma_d + \gamma_h$ is preferred.

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