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Citation: Appl. Phys. Lett. 91, 151105 (2007); doi: 10.1063/1.2795798
View online: http://dx.doi.org/10.1063/1.2795798
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v91/i15
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Nanocrystals in silicon photonic crystal standing-wave cavities as spin-photon phase gates for quantum information processing

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(Received 1 June 2007; accepted 19 September 2007; published online 9 October 2007)

By virtue of a silicon high-Q photonic crystal nanocavity, we propose and examine theoretically interactions between a stationary electron spin qubit of a semiconductor nanocrystal and a flying photon qubit. Firstly, we introduce, derive, and demonstrate the explicit conditions toward realization of a spin-photon phase gate, and propose these interactions as a generalized quantum interface for quantum information processing. Secondly, we examine single-spin-induced reflections as direct evidence of intrinsic bare and dressed modes in our coupled nanocrystal-cavity system.


Cavity quantum electrodynamics (QED) provides an almost ideal system for implementing quantum information and computation.1–5 Recently, photonic crystal nanocavities with high quality factors (Q) and ultrasmall mode volumes are attracting attention in the context of optical cavity QED.6–9 Strong interactions between a quantum dot and a single photonic crystal cavity have been observed experimentally.6–9 Moreover, single photons from a quantum dot coupled to a source cavity can be transferred to a target cavity via an integrated waveguide in an InAs/GaAs solid-state system,10 which opens the door to construct the basic building blocks for future chip-based quantum information processing systems. Weak coupling nanocrystal ensemble measurements were reported in TiO2–SiO2 and AlGaAs cavity systems (below 1 μm wavelengths) recently11,12 and also independently in silicon nanocavities with lead chalcogenide nanocrystals at near 1.55 μm fiber communication wavelengths recently.13 In this letter, we examine the single-photon pulse (or weak coherent light pulse) interactions of a single semiconductor nanocrystal in a system comprised of standing-wave high-Q/V silicon photonic crystal nanocavities. In contrast to earlier traveling-wave whispering gallery mode cavity studies,14 we show here that a QED system based on coupled standing-wave nanocavities can realize a spin-photon phase gate even under the bad-cavity limit and provide a generalized quantum interface for quantum information processing. In addition, we demonstrate numerically a solid-state universal two-qubit phase gate operation with a single qubit rotation. This theoretical study is focused within the parameters of near 1.55 μm wavelength operation for direct integration with the fiber network, and in the silicon materials platform to work with the vast and powerful silicon processing infrastructure for large-array chip-based scalability.

We begin by considering a combined system consisting of coupled point-defect high-Q/V photonic crystal cavities, a line-defect photonic crystal waveguide, and an isolated single semiconductor nanocrystal. We offer some brief remarks on this system before building our theoretical model. When a photon pulse is coupled into the cavity mode via a waveguide [Fig. 1(a)], photons can couple out of the cavity along both forward and backward propagating directions of the waveguide because the cavity supports standing-wave modes. While each cavity can each have a Faraday isolator to block the backward propagating photon, such implementation may not be easily scalable to a large array of cavities. To obtain only forward transmission, here we examine theoretically a defect cavity system with accidental degeneracy15–17 as a generalized study of cavity-dipole-cavity systems, and which also provides close to 100% forward-only drop efficiency. This framework is also immediately applicable to nonreciprocal magneto-optic cavities which have larger fabrication tolerances.18 Both systems sup-

FIG. 1. (Color online) (a) Sketch of a waveguide side coupled to a cavity which supports two degenerate modes $c_1$ and $c_2$, with opposite parity. (b) Lead chalcogenide (e.g., lead sulphide) nanocrystal energy levels and the electron-exciton transitions in the presence of a strong magnetic field along the waveguide direction, which produces nondegenerate transitions from the electron spin states $|↑\rangle$ and $|↓\rangle$ to the charged exciton states $|e_1\rangle$ and $|e_2\rangle$ under the transition selection rules.
port two degenerate even $|e\rangle$ and odd $|o\rangle$ cavity modes ($h$ polarized, dominant in-plane $E$ field) that have opposite parity due to the mirror symmetry, as shown in Fig. 1(a). The waveguides can support both $v$ polarizations (dominant in-plane $H$ field) and $h$ polarizations for polarization diversity.19

Figure 1(b) shows the energy levels and electron-exciton transitions of our cavity-dipole-cavity system. In order to produce nondegenerate transitions from the electron spin states, a magnetic field is applied along the waveguide direction.20 [1] and [2] play the role of a stationary qubit, which have shown much longer coherence time than an exciton (dipole or charge). The transition $|\uparrow\rangle \leftrightarrow |\downarrow\rangle$, with the descending operator $\sigma_-=|\downarrow\rangle\langle\uparrow|$, is especially chosen and coupled with the cavity modes with single-photon coupling strengths $g_o(r)$ and $g_e(r)$, while other transitions are decoupled with the cavity modes.

Now we construct our model by studying the interaction between the nanocrystal and the cavity modes. The Heisenberg equations of motion for the internal cavity fields and the nanocrystal are

$$\frac{dE_p}{dt} = -i[H_p, E] - \kappa_p E_p + \Delta_p \sum_{j=1,2} \sqrt{\kappa_p} c_{in}^{(j)} \ , \quad (1)$$

$$\frac{d\sigma_\pm}{dt} = -i[\sigma_\pm H] - \gamma \sigma_\pm \ , \quad (2)$$

where $\Delta_p = i$ and $\lambda_p = (-1)^j + 1$, and the interaction Hamiltonian $H = \Delta_p \sigma_\pm + \sum_{j=1,2} g_{\pm}^{(j)} c_{in}^{(j)} + g_o(r) c_e \sigma_\pm + h.c.$ is in a rotating frame at the input field frequency $\omega_0$. In contrast to earlier work,14,21,22 here we examine the case with the two $|e\rangle$ and $|o\rangle$ modes in the standing-wave cavities in order for forward-only propagation of the qubit. The cavity dissipation mechanism is accounted for by $\kappa_{e(o)} = \kappa_{e(o)}^{\text{in}} + \kappa_{e(o)}^{\text{out}}$, where $\kappa_{e(o)}^{\text{in}}$ is the intrinsic loss and $\kappa_{e(o)}^{\text{out}}$ the external loss for the even (odd) mode. The nanocrystal dissipation is represented by $\gamma = \gamma_e/2 + \gamma_o$, where $\gamma_e$ is the spontaneous emission rate and $\gamma_o$ the dephasing rate of the nanocrystal.

When the two degenerate modes have the same decay rates, i.e., $\kappa_o = \kappa_{e(o)}^{\text{in}} = \kappa_0$, $\kappa_e = \kappa_{e(o)}^{\text{out}} = \kappa_1$, and $\lambda = \kappa_1 + \kappa_0$, two new states $|\pm\rangle=|(e\pm o)\rangle/\sqrt{2}$ are suitable to describe this system, which can be thought of as two traveling (or rotating) modes. In this regard, the interaction Hamiltonian is expressed as $H = \Delta_\parallel \sigma_\parallel + \sum_{j=1,2} \Delta_j \sigma_j + g_o(r) c_e \sigma_\parallel + h.c.$, where the effective single-photon coupling rates are $g_{\pm}^{(j)} = |g_{\pm}^{(j)}(r)|/\sqrt{2}$ in this case, Eqs. (1) and (2) are rewritten into the corresponding forms with $c_{\pm}$.

The nanocrystal-cavity system is excited by a weak monochromatic field (e.g., single-photon pulse), so that we solve the above motion equations with

$$\sigma_- (\omega) = -i \sum_{x=x_,+} g_x (r) c_x (\omega) / (i \delta + \gamma) \ , \quad (3)$$

c and $c_e (\omega)$ are given as

$$i \sqrt{2\kappa} c_{in}^{(1,2)}(\omega) - (i \delta + \kappa) c_e (\omega) - i g_o^*(r) \sigma_+ (\omega) = 0 \ . \quad (4)$$

Note that orthogonality of the $|e\rangle$ and $|o\rangle$ basis modes [as shown in Fig. 1(a)] forces the nanocrystal to choose only either $g_o(r) = +i g_o(r)$ or $g_o(r) = -i g_o(r)$, or both (in which cases $|e\rangle$ and $|o\rangle$ are uniquely zero), but no other possibilities. Photons input from only the left waveguide forces only one of the cavity states $(|e\rangle + |o\rangle)/2$ to exist,15 and we assume this cavity environment from the existing photon qubit enhances the $g_o(r) = -i g_o(r)$ probability. Of course, with only the left waveguide qubit input in a nonreciprocal magneto-optic cavity, this condition is strictly enforced. Hence we can take $g_o(r) = -i g_o(r)$, which implies $g_o(r) = 0$ and $g_o(r) = 2g_e$, to further simplify Eq. (4). Now note that the left output $c_{out}^{(1)}$ remarkably vanishes, while the right output is given by $c_{out}^{(2)} = c_{out}^{(1)}(\kappa - 2\kappa_1 - i\delta + \lambda) / (\kappa - i\delta + \lambda)$, where $\lambda = 2|g_o(r)|^2 / \sqrt{(\Delta - \delta + \gamma)^2}$, and $\Delta = \delta - \delta_\parallel$ and $\delta = -\delta_\parallel$ denote the nanocrystal-cavity and input-cavity detunings, respectively. Importantly, this implies that our quantum phase gate provides a true one-way transmission through the cavity-dipole-cavity system.

To examine more of the underlying physics, we consider first the case of exact resonance ($\Delta = 0$, $\delta = 0$). When $|g_o(r)|^2 / \kappa \gg 1$ (the nanocrystal occupies the spin state $|\uparrow\rangle$), we obtain $c_{out}^{(2)} = c_{in}^{(1)}$. When $g_o(r) = 0$ (the nanocrystal occupies the spin state $|\downarrow\rangle$), we obtain $c_{out}^{(2)} = -c_{in}^{(1)}$ for $\kappa_1 \gg \kappa_0$, which indicates that the system achieves a global phase change $e^{i\gamma}$. This distinct characteristic allows the implementation of a spin-photon phase gate. After the photon pulse passes though the cavity system, we easily obtain a gate operation, $|h\rangle |\uparrow\rangle \rightarrow |h\rangle |\uparrow\rangle$, $|h\rangle |\downarrow\rangle \rightarrow -|h\rangle |\downarrow\rangle$, $|v\rangle |\downarrow\rangle \rightarrow -|v\rangle |\downarrow\rangle$. This two-qubit phase gate combined with simple single-bit rotation is, in fact, universal for quantum computing. More importantly, this interacting system can be regarded as a quantum interface for quantum state sending, transferring, receiving, swapping, and processing.

To efficiently evaluate the quality of the gate operation, the gate fidelity is numerically calculated, as shown in Fig. 2. Considering specifically a lead chalcogenide (e.g., lead sulfide) nanocrystal and silicon photonic nanocavity systems for experimental realization, we choose the spontaneous decay as $\gamma_e \sim 2$ MHz and all nonradiative dephasing $\gamma_o \sim 1$ GHz at cooled temperatures. Photonic crystal cavities have an ultrasmall mode volume $V$ ($\sim 0.1 \mu m^3$ at 1550 nm), with a resulting calculated single-photon coherent coupling rate $|g_\parallel| \sim 30$ GHz. High $Q$’s of up to even $\sim 10^9$ experimentally and $\sim 10^7$ theoretically23,24 have been achieved in photonic crystal cavities.

With these parameters, as shown in Fig. 2(a), the gate fidelity of the cavity-dipole-cavity system can reach 0.98 or more, even when photon loss is taken into account, and even when the vacuum Rabi frequency $g_o$ is lower than the cavity decay rate $\kappa$ (bad-cavity limit). The gate fidelity increases initially as the cavity approaches more into the overlapping
The authors acknowledge funding support from the National Science Foundation (ECS-0622069), DARPA, and the New York State Office of Science, Technology and Academic Research. X. Yang acknowledges support of an Intel Fellowship. Y.-F. Xiao and G.-C. Guo are funded by National Fundamental Research Program of China.

1 See, for example, H. Mabuchi and A. C. Doherty, Science 298, 1372 (2002), and references therein.
2 See, for example, G. Khitrova, H. M. Gibbs, M. Kira, S. W. Koch, and A. Scherer, Nat. Phys. 2, 81 (2006), and references therein.