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Scheme for Coherent Control of Vacuum Rabi Oscillations in a Quantum Dot-Cavity System using Geometric Phases

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Abstract

We propose a scheme for coherent control of a strongly-coupled quantum dot-cavity system based on geometric phases. We numerically show that vacuum Rabi oscillations can be robustly inverted by irradiating a 2π-laser pulse. A cyclic evolution of a quantum dot exciton via a biexciton state is induced by the pulse and provides a quantized Berry phase to the system. The inversion operation exhibits tolerance against errors in pulse area of the irradiated pulse. For example, a robust oscillation inversion was found possible even under the presence of ±20% deviations in pulse area from the optimal condition. For further applying the proposed scheme, we also show that the oscillations can be effectively limited by periodic irradiation of inverting pulses. Our approach using geometric phases will be useful for implementing quantum devices based on robust and ultrafast coherent control of strongly-coupled quantum dot-cavity systems.

1. Introduction

The coherent interactions between quantum emitters and cavity photons in solid-state cavity quantum electrodynamics (CQED) systems play an important role for stable and scalable quantum information processing(QIP). Among investigated CQED systems, strongly-coupled quantum dot(QD)-micro/nanocavity systems are one of the most promising platforms due to their capability of operation at telecommunication wavelengths as well as of integration into quantum photonic integrated circuits. Although coherent control of the QD-cavity systems is required for various quantum devices[1,2], earlier approaches predominantly relied on dynamic control of the quantum systems[3], which is in general sensitive to random fluctuations and systematic errors in control parameters. These drawbacks will be a main obstacle for the realization of highly-reliable and large-scale QIP systems.

One of the alternative approaches to dynamic control is to use geometric phases. A geometric phase is determined only by geometrical properties of a quantum operation, providing it certain fault-tolerance[4]. So far, the effectiveness of the geometric operation has been demonstrated in various quantum systems[5-7]. Similarly, in QD-cavity coupled systems, theoretical analyses for geometric phase gate operations using a dispersive QD-cavity interaction have been reported[8]. However, there has been no proposal of coherent control of strongly-coupled QD-cavity systems using geometric phase.

In this study, we present a method for geometric-phase-based coherent control of vacuum Rabi oscillations in a strongly-coupled QD-cavity system. We numerically demonstrate robust inversion of the oscillations by inducing the transition between a QD exciton and a biexciton with a 2π rotation pulse. This operation provides a geometric phase of π to the exciton state and hence inverts the phase of the oscillation. We found that this geometric operation is immune to errors in the irradiated pulse. For example, faithful oscillation inversions are computed even under the presence of ± 20% deviation in pulse area from the optimal condition. We also show that it is possible to effectively restrict the vacuum Rabi oscillations by periodically irradiating the flipping pulses.

2. Model

Figure 1 (a) shows a schematic of the investigated QD-cavity coupled system. We consider a three-level-system in the QD consisting of the grand state |G>, an exciton state |X> and biexciton state |XX> with a biexciton binding energy of χ = 1500 μeV. The cavity is coupled to the QD system with a realistic coupling strength of g=18 μeV[9], and is resonant with the |G>↔|X> transition. The incoherent processes including cavity photon leakage (κ = 1 μeV), QD's spontaneous decay (γ = 0.13 μeV) and QD's pure dephasing (γ_{ph} = 2 μeV) are also considered. We employed a quantum master equation for calculating time evolutions of cavity photon number.

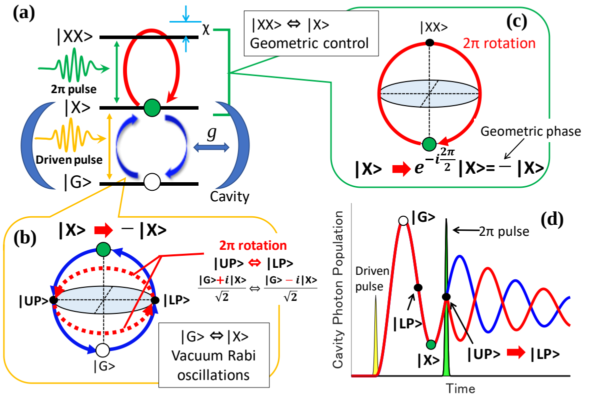

Fig. 1 (a) Sketch of the investigated strongly-coupled QD-cavity system. (b) Bloch sphere representation of vacuum Rabi oscillations between an excitonic |G>↔|X> transition and a cavity photon. UP (LP) represents the upper (lower) polariton. (c) Geometric operation for the |X>↔|XX> transition. 2π rotation provides a geometric phase of π to |X> state and induces a |UP>↔|LP> transition in (b) (d) Time evolution of cavity photon population with (red line) and without (blue line) the 2π-pulse (green pulse) at the system being |UP>. Corresponding |G>↔|X> transition in (b) is plotted on the population.

Here, we describe the flow of coherent control of vacuum Rabi oscillations using geometric phase. In the first step, we trigger vacuum Rabi oscillations by a gaussian-shaped a laser π-pulse (pulse width = 5 ps) that is resonant with the |G>↔|X> transition (Fig.1 (b)) is irradiated to initiate vacuum Rabi oscillations. Then, for the geometric operation, we resonantly excite the |X>↔|XX> transition by a control pulse with a pulse area of $\theta = 2\pi$. After a cyclic evolution of the exciton between |X>↔|XX> transition in the Bloch sphere (Fig. 1(c)), |X> state acquires a geometric phase of π, which corresponds to a phase flip from |X> to -|X>. This phase change of |X> causes a direct transition from the upper polariton (UP) and lower polariton (LP) (Fig.1(b)). Consequently, when we apply the 2π-pulse when the system is at |UP> state (Fig. 1(d)), the vacuum Rabi oscillation can be inverted due to the transition from |UP> to |LP>.

3. Numerical Results

Figures 2 (a)-(d) show calculated time evolutions of cavity photon population when the control 2π pulse is applied at four different states of the oscillations (|LP>, |X>, |UP> and |G>, respectively). As we expected, the Rabi oscillations are faithfully flipped just after the arrival of the 2π-control pulse when the system is either at the |LP> or |UP> state (Fig. 2 (a) and (c)). On the other hand, for the pulse irradiation at the system being |X> or |G> state (Fig. 2 (b) and (d)), the oscillations are unaffected, because the phase flip of |X> or |G> does not affect the vacuum Rabi oscillation dynamics. Note that we also confirmed that it is difficult to implement the same flipping action on the oscillations by the dynamic control with a resonant π-pulse to the G-X transition.

In order to investigate the robustness of the geometric operation for the oscillation inversion, we examined various pulse area of the control pulse (θ), with fixing the pulse width to be 5 ps. Figures 2 (e)-(g) show examples when varying θ from 0.8 to $1.2\theta_0$, where θ_0 is the optimum pulse area of 2π. Faithful oscillation inversions can be seen even with ±20% errors in pulse areas. With further increasing the error in θ, damping and time-delay of oscillations gradually appear.

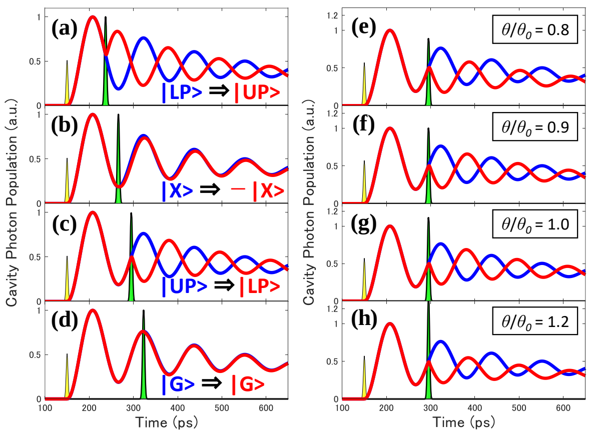

Fig. 2 Calculated cavity photon populations with a control pulse irradiated respectively at the system being (a) |UP>, (b) |X>, (c) |LP> and (d) |G> and (e)-(h) with unoptimized control pulses of $\theta_0/2\pi$ = 0.8, 0.9, 1.0 and 1.2. Blue solid lines are results without the control pulses. Yellow pulse is the π-pulse triggering the oscillations.

These results suggest that our scheme based on geometric phases will be advantageous for implementing robust control of the vacuum Rabi oscillations under the existence of fluctuations in control parameters.

Finally, we show that the inversion operation using geometric phases can be used for a more sophisticated control of vacuum Rabi oscillations. Figures 3(a) and (b) exhibit the calculated oscillations with four control 2π-pulses periodically irradiated when the system is in |UP> or |LP> state during the oscillations. The vacuum Rabi oscillation is limited in the upper (Fig. 3(a)) or lower (Fig. 3(b)) half of the oscillation. From this result, we expect that the multiple reversing-pulse operation can also be a powerful scheme for coherent control of the QD-cavity systems.

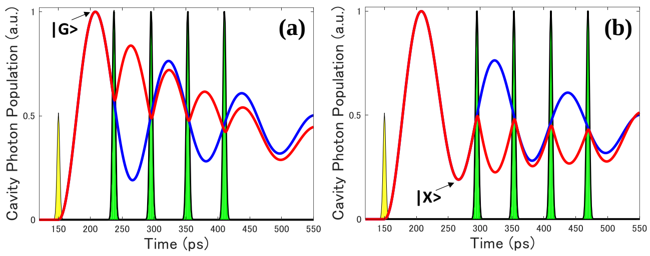

Fig. 3 Calculated vacuum Rabi oscillations when the four control pulses (green pulses) are periodically applied at the system being (a) |LP> and (b) |UP> states (red lines). Blue solid lines are the oscillations without the control pulses.

4. Conclusions

We proposed a simple and fault-tolerant scheme for coherent control of vacuum Rabi oscillations in a strongly-coupled QD-cavity system by using geometric phase. The oscillations can be robustly flipped by applying a 2π rotation pulse to an QD exciton. We found that the faithful oscillation inversion can be implemented even with ±20% errors in pulse area from the optimal condition. We also showed that the periodic irradiation of the reversing-pulses enables effectively limit the vacuum Rabi oscillations. Our approach will be useful for implementing robust and ultrafast quantum operation on strongly-coupled QD-cavity systems.

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References

[1] A. Faraon *et al.*, Nat. Phys. 4, 859 (2008).
[2] H. Kim *et al.*, Nat. Photonics 7, 373 (2013).
[3] R. Bose *et al.*, Nat. Photonics 8, 858 (2014).
[4] E. Sjöqvist, Physics 1, 35 (2008).
[5] D. Leibfried *et al.*, Nature 422, 412 (2003).
[6] A.A. Abdumalikov Jr *et al.*, Nature 496, 482 (2013).
[7] Y. Sekiguchi *et al.*, Nat. Photonics 11, 309 (2017).
[8] J.-Q. Zhang *et al.*, J. Opt. Soc. Am. B 28, 1959 (2011).
[9] K. Kuruma *et al.*, Phys. Rev. B 97, 235448 (2018).