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Entanglement of Quantum Dot States and Correlation Properties of Cavity Photons Emitted by Coupled Quantum Dot Qubits

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ABSTRACT We have studied the entanglement of coupled quantum dot qubits via cavity photon correlation. In the case of conservation of total entanglement, we have found that in the strong coupling limit of the cavity quantum dot qubit interactions guided an alternative means of preserving entanglement. In the case of cavity photon and quantum dot excitation dynamics coupled with surface plasmons optically excited by laser pulse. It was found the character of the quantum entanglement formation was different in strong and weak coupling regimes between the photons and quantum dots. It was found that the cavity photons were sensitive to the quantum dot concurrence formation. The effect of the entanglement oscillations between the quantum dot and the cavity photons due to the excitation polariton formation was found. In the time intervals between the peaks, the photons emitted by the entangled quantum dots strongly anti-bunched. This behavior contrasted for unentangled quantum dots enabled direct optical detection of quantum dot qubit entanglement. The correlation exhibited in quantum dot photon cavity system. It was found that the second order correlation function of photon emitted by coupled quantum dot qubits were utilized as a quantum entanglement formation. Various quantum dot coupling methods have been considered including sharing the photon field in an optical microcavity. We have used an alternative system for achieving, detecting and study of entanglement of palsmonically coupled quantum dots in optical microcavities using numerical simulations and theoretical analysis we have presented one to one correspondence between the entanglement of quantum dot states and the correlation properties of cavity photons emitted by the quantum dots. We have shown that the time dependent of both the quantum dot entanglement and the photon correlation functions changed from photon correlation suppressed to strong oscillation during the transition from weak to strong quantum dot cavity photon coupling regimes. The results found were in good agreement with previously obtained results.

KEYWORDS Entanglement, Coupled Quantum Dot, Correlation, Cavity Photon, Excitation, Plasmon, Oscillation, Polariton, Qubit, Simulation.

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INTRODUCTION

Hou et al. [1], Otten et al. [2,3] and Thorgrinsson et al. [4] studied solid state realization of trapped atoms, coupled quantum dot qubits or artificial molecules, in a dissipative environment to produce entanglement and multi dip systems at liquid helium temperature. This was validated experimentally, potentially opened a new route to the design of robust solid state emitters of entangled photons of relivance to quantum information science an sensing. Burkan, Loss and Divincenzo [5] studied coupled quantum dots as a platform for the design of quantum gates was used in prospective quantum computers. Blais et al. [6] presented the coupled quantum dot system in high quality cavity was mapped into cavity quantum electrodynamics of super-conducting electrical circuits. Watson et al. [7] showed that a programmable two qubit quantum processor has been realized based on two quantum dots in silicon. Thearle et al. [8] presented the developments in quantum cryptography, quantum communications and quantum simulations. Liao et al. [9] presented low-earth-state transmission which provided the route to secure quantum internet a hundred kilometer long optical line for quantum distribution. Keilly [10] and Pan et al. [11] presented advances for simulating into systems that provided physical realizations of quantum entangled states. O'Corner et al. [12] and Hua et al. [13] provided techniques including coupled quantum rings, quasi phase matching ring crystals for entangled photon generation and sub-radiant Dicke states of trapped interacting atoms [14-15]. Dumitrescu and Lawrie [16] has numerically analysed the anti-bunching of photons emitted by the quantum dots. Geis et al. [17] showed that various quantum dot coupling methods have been provided the sharing the photon field in an optical micro cavity. The other investigators [18-19] presented the bunching and anti-bunching behavior were different from that which leaded to the bunching behavior for coupled plasmonic system due to their bosonic character and ultra-strong coupling bunching behavior. Shah et al. [20] presented that temporal evolution of the whole system was described by the cavity quantum electrodynamics equation for time dependent density operator for two level quantum dots surface plasmon and cavity photon cavities. Otten et al. [21] numerically solved in the rotating phase approximation with developed opened quantum system in simulation package based on square matrix vector multiplication algorithms along with the fourth order Range Kutta numerical scheme. It was found that the results converged for the number of photon levels and the number of plasmon levels. Wooters [22] studied that the quantum dot entanglement was captured via concurrence and calculated from the quantum dot reduced density matrix. Galfsky et al. [23] studied that photonic cavity environment as powerful means for controlling light matter interactions in solid state systems. Variations in the cavity geometry, the cavity quantum dot energy detuning and the quantum dot position relative to the maximum of the light electric field in the cavity and to the plasmonic structure provided experimental opportunity to alter the quantum dot cavity photon and quantum dot surface plasmon interaction strengths in wide limits [24-26].

METHOD

We have considered a system composed of two quantum dot qubits coupled with a common surface plasmon mode. Each quantum dot was also coupled to a separate photonic cavity mode. Cavity quantum electrodynamics calculations were made which was presented upon optical excitation by a femto second laser pulse, entanglement of the quantum dot excitations occurred and time variation of the g pair correlation function of the cavity photon was an indicator of the entanglement. The system was composed of two quantum dots embedded into optical cavities. The quantum dot electronic degree of freedom were coupled with the surface plasmon modes in a neighboring metal surface or nano sphere. The cavity quantum electrodynamics equation for time dependent density operator was used

$$\frac{\partial \hat{p}}{\partial t} = \frac{-i}{\hbar}\left[\hat{H}, \hat{p}\right] - \frac{i}{\hbar}\left[\hat{H}_d, \hat{\rho}\right] + L\left(\hat{\rho}\right)$$

Where $\hat{H} = \hat{H}_0 + \hat{H}_{\text{int}}$ is the system Hamiltonian which included the free Hamiltonians of two $\left(i = 1, 2\right)$ levels quantum dots surface plasmon and cavity photon modes given as

$$\hat{H}_0 = \sum_i \hbar\omega_i \hat{\sigma}_i^\dagger \sigma_i + \hbar\omega_s \hat{b}^\dagger \hat{b} + \sum_i \hbar\omega_i \hat{c}_i^\dagger \hat{c}_i$$

And their interaction was

$$\hat{H}_{\text{int}} = \sum_i \hbar g_s^i \left(\hat{\sigma}_i^\dagger \hat{b}_i + \hat{\sigma}_i \hat{b}_i^\dagger\right) - \sum_i \hbar g \left(\hat{\sigma}_i^\dagger \hat{c}_i + \hat{\sigma}_i \hat{c}_i^\dagger\right)$$

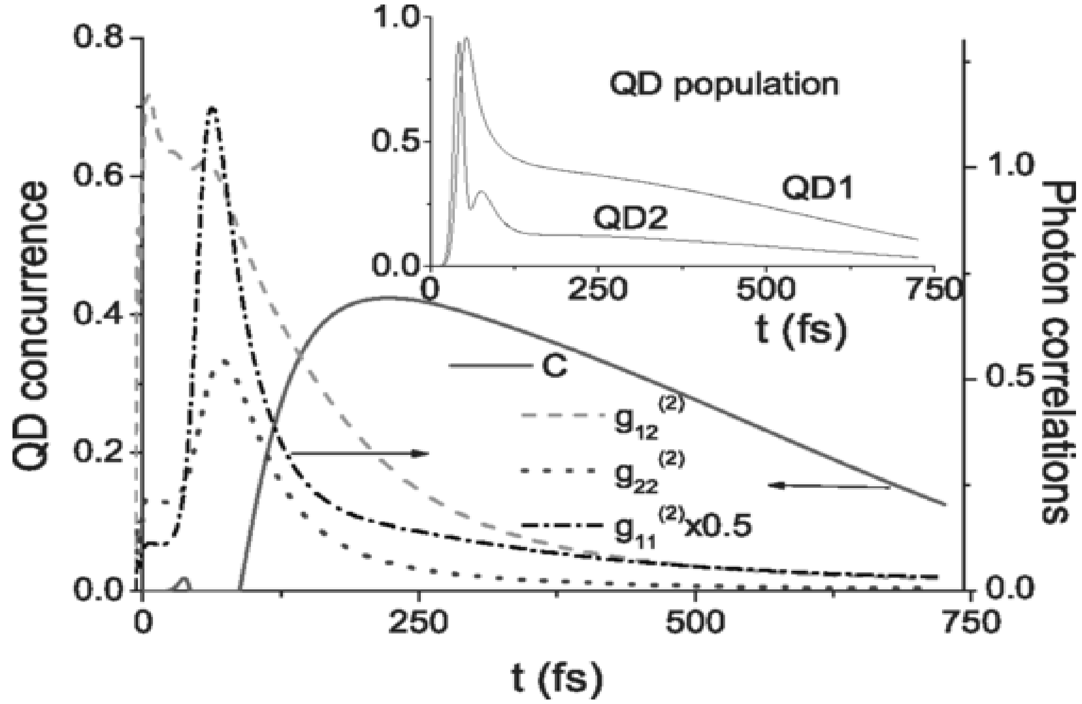
And coupling was

$$\hat{H}_d = -E(t)\left[\sum_i d_i\left(\hat{\sigma}_i + \hat{\sigma}_i^\dagger\right) + d_s\left(\hat{b} + \hat{b}^\dagger\right)\right]$$

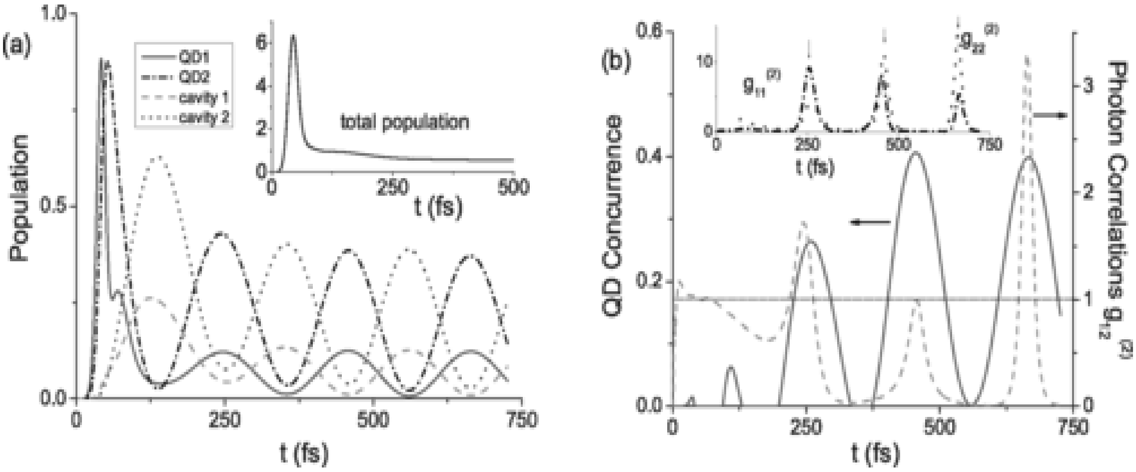
Where $E(t)$ is the electromagnetic field in the semiclassical dipole limit, $\hat{\sigma}_i, \hat{b}$ and $\hat{c}_L$ are the respective annihilation operators for quantum dots, plasmon, and cavity photon excitations, d_i and d_s are the transition dipole moments of the quantum dots and plasmon. The annihilation operators act in the coordinate space, whereas the total electron excitation and phonon wave functions obeyed he conventional symmetry. The coordinate wave functions are symmetric and antisymmetric. The Lindblad super operator $L(\hat{p})$ accounts for the quantum dot and cavity photon population relaxation and dephasing and plasmon dissipation. The quantum dot entanglement was captured through wooters concurrence $c(t)$ was calculated from the quantum dot reduced density matrix.

RESULTS AND DISCUSSION

Graph (1) shows the plot of dynamics of the system for weak quantum dot cavity photon coupling. The study of quantum dynamics of pulsed system in the weak coupling for the quantum dot photonic cavities results are shown in the Graph (1). The inset of Graph (1) shows that the initial quantum dot population oscillations damped at 100 fs after the system was excited by the laser pulse after the system was excited by the laser pulse and at later time the quantum dot populations were not equal to each other due to the difference in the quantum dot plasmon coupling strengths. This resulted symmetry of the quantum dot entanglement. Graph (1) shows the both the cross and same cavity correlated g_{ij} of the photon decrease. Graph (2) shows the plot of dynamics of the system in the strong coupling regime. Graph (2) shows the results found for large coupling. Graph (2) (a) shows that after excitation both the quantum dot and cavity photon populations produced oscillations. The inset of graph (2) (a) shows that the total population did not appear significant oscillations. Graph (2) (b) shows the formation of oscillations of the quantum dot concurrence $c(t)$ that accompanied the population oscillation in Graph (2) (a). The Graph (2) (b) also revealed that after the initial period of relaxation the cavity photon cross-correlation function created oscillation that were synchronous with the quantum dot concurrence oscillations. The sharp spikes on $g_{12}(t)$ curve were positioned at the same moments, when concurrence reached its maxima. Graph (2) (b) also shows that correlation functions for the same cavity photon modes followed a similar pattern. The obtained results were compared with previously obtained results of theoretical and experimental research works and were found in good agreement.



Graph 1: The Plot of dynamics of the system for weak quantum dot cavity photon coupling.



Graph 2: Plot of oscillatory dynamics of the system in the strong coupling regime.

CONCLUSION

We have studied entanglement of quantum dot states and correlation properties of cavity photons emitted by coupled quantum dot qubits. It was found that second order correlation function of photons emitted by coupled quantum dot qubits was utilized as quantum entanglement formation. Various quantum dot coupling methods have been considered including the sharing the photon field in an optical micro cavity considering numerical simulations and theoretical analysis. We have presented one to one correspondence between the entanglement of quantum dot states and the correlation properties of cavity photons emitted by the quantum dots. It was shown that the time dependence of both the quantum dot entanglement and the photon correlation functions was changed from photon correlation suppression. It was found that the quantum simulations, quantum cryptography and quantum communications relied on quantum entanglement formation. We have considered a system composed of two quantum dot qubits coupled with common damped surface plasmon mode and each quantum dot was also coupled to a separate photonic cavity mode. The oscillations of entangled exciton polariton states in which quantum correlations were shared between the quantum dot excitons and cavity photons. The results found enabled the identification of entanglement in coupled quantum dot system through cavity photon correlation results. The obtained results were found in good agreement with previously obtained results.

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