Quantum Information and Computation, Vol. 11, No. 5&6 (2011) 0456–0465

QUANTUM MEMORY FOR LIGHT WITH A QUANTUM DOT SYSTEM COUPLED TO A NANOMECHANICAL RESONATOR

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Received June 29, 2010
Revised February 1,2011

The specific features including high factor and long vibration lifetime of nanomechanical resonator (NR) in nano-optomechanical systems have stimulated research to realize some optical devices. In this work, we demonstrate theoretically that it is possible to achieve quantum memory for light on demand via a quantum dot system coupled to a nanomechanical resonator. This quantum memory for light is based on mechanically induced exciton polaritons, which makes the dark-state polariton reaccelerated and converted back into a photon pulse. Our presented device could open the door to all-optical routers for light memory devices and quantum information processing.

Keywords: Quantum memory, Quantum Dot, Nanomechanical resonator

Communicated by: S Braunstein &R Laflamme

1. Introduction

For a long time, the ability to achieve the light memory has been considered as one of the most exciting emergent topics in optics[1]. There are several experimental demonstrations showing the capability to slow down light more than six orders of magnitude in a variety of media ranging from atomic vapor[2], doped solid[3], to quantum cavity[4]. These results have led to intensive research into new materials, devices, and system studies that examine their impact to new applications[5, 6]. It is believed that electromagnetically induced transparency (EIT)[7], coherent population oscillation (CPO)[8], Raman and Brillouin amplification[9] are commonly used techniques to control the group velocity in nanostructure system. Some of the EIT based coherent effects which are present in a Rb vapor[10, 11] and dilute systems[12] have been investigated theoretically and experimentally in semiconductors. Unlike the slow light via EIT,, which is dominated by the coherence dephasing time, CPO is governed by the population relaxation time and becomes nearly insensitive to temperature[13]. In addition, CPO is weakly influenced by inhomogeneous broadening in atomic systems in contrast to the quantum coherence effect involved in EIT. Slow light at room temperature originated by CPO has been experimentally observed in silicon photonic crystals[14], erbium doped fibers (EDFs)[15], photorefractive materials[16], and biological thin films[17].

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However, the major importance for implementing these light storage devices in precision measurements and quantum computing tasks, obviously, is achieving long lifetimes of coherence[18]. This requires to seek some special materials, which have relatively long coherence lifetime or elimination of decoherence arising from inhomogeneous external fields and trapping potentials. In atomic system, long coherence times have been observed using clock transitions[19], which are first-order insensitive to magnetic fields. With this backdrop, in this work, we theoretically demonstrated the possibility of light storage and retrieval with a quantum dot(QD) embedded in a nanomechanical resonator (NR). In this quantum process, it is the long lifetime of nanomechanical resonator that provides the long time of mechanical vibration, and results in long time coherence with quantum optical field. Besides, bestriding the realms of classical and quantum mechanics, NR has limited environment, small size, high Q factor and long vibration lifetime, and offers great promise for a huge variety of applications and fundamental research[20]. There has been a flurry of activity aiming at the development of nanomechanical resonator[21] and its coupled system[22], such as the detection of qubit-oscillator entanglement in nanomechanical systems by coupling a superconducting qubits [23], the investigation of dynamical properties of a vibrating molecular quantum dot in a Josephson junction[24], and cooling the vibrations of a nanotubes with constant electron current[25]. Recently, Bennett *et al.*[26] have experimentally studied the strong coupling effects in an electromechanical system consisting of a quantum dot and a mechanical resonator. But the potentialities for NR's light storage remain unexplored to date.

In our previous work, we have theoretically achieved the slow light and fast light in this coupled nanomechanical resonator-quantum dot system according to mechanically induced coherent population oscillation (MICPO) principle[27]. In the present article, we further investigate this promising system and demonstrate that it is possible to store and read out the quantum signal pulse by switching off and on the pump pulse. Theoretical analysis shows that the vibration of NR leads to the dressed metastable energy level of quantum dot, which provides a temporary accommodation for electrons. This dressed exciton dark-state polaritons can be reaccelerated and converted back into a photon pulse via a tunable pump laser. Thanks to the long lifetime of NR, the signal pulse can stay for a long time compared with other semiconductor systems.

2. Theory

As in our previous work[27], we consider a system composed of a two-level semiconductor quantum dot and a nanomechanical resonator in the simultaneous presence of a strong pump field and a weak signal field. Recently, this two-laser technique has been experimentally demonstrated by Kippenberg *et al.* in radiation-pressure coupling of an optical and a mechanical mode system. They predicted that this technique can be used for slowing and on-chip storage of light pulses in the future[28].

At low temperatures, the two-level semiconductor quantum dot consists of the ground state $|g\rangle$ and the first excited state (single exciton) $|e\rangle$ [29, 30]. The quantum dot via exciton interacts with a strong pump field (ω_p) and a weak quantum signal field (ω_s). Such NR-QD system has been experimentally demonstrated by Bennett *et al.*[26] using atomic force microscope (AFM) to probe quantum electronic systems. As usual, the two-level quantum dot system can be characterized by the pseudospin $-1/2$ operators $S^{\pm}$ and S^z. The energy level

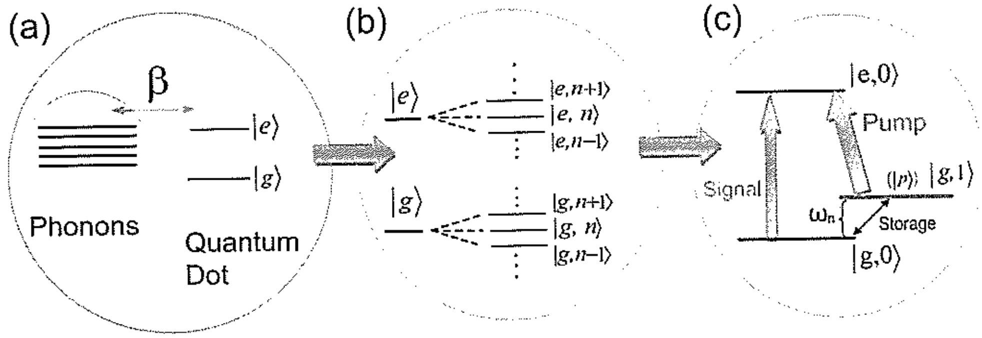

Fig. 1. (a) The initial model of a two-level quantum dot and a nanomechanical resonator(NR). $|g>$ and $|e>$ are the ground state and excited state of quantum dot, respectively, β is the coupling between the quantum dot and the nanomechanical resonator. The vibration modes of NR are treated as phonons modes. (b) The split energy levels of quantum dot when dressing NR. $|g, n> = |g> |n>$ and $|e, n> = |e> |n>$ where $|n>$ denotes the number states of the nanomechanical resonator. (c) The process of quantum memory for light, where the $|g, 1> \rightarrow |e, 0>$ and $|g, 0> \rightarrow |e, 0>$ transitions can be induced by the pump beam and signal beam respectively. $|g, 1>$ denoted by $|p>$ is the metastable state caused by mechanically vibration. The signal pulse is temporarily stored in the state between $|g, 1>$ and $|g, 0>$.

configuration of this coupled NR-QD system is sketched in Fig.1(a). Then the Hamiltonian of this two-level exciton can be described as $H_{ex} = \hbar\omega_{ex}S^z$, where ω_{ex} is the frequency of exciton. Besides, we assume the doubly clamped suspended nanomechanical resonator vibrates in its fundamental mode [31]. The lowest-energy resonance of NR corresponds to the fundamental flexural mode with the frequency ω_n and the resonator is assumed to be characterized by sufficiently high quality factors [31]. The eigenmode of NR can be described by a quantum harmonic oscillator, with b and b^+ the bosonic annihilation and creation operators of energy $\hbar\omega_n$. The Hamiltonian of NR is given by $H_n = \hbar\omega_n b^+ b$.

In the simultaneous presence of a strong pump field and a weak signal field, the Hamiltonian of the total system can be written as [31, 32]

$$H_t = H_{ex} + H_n + H_{ex-n} + H_{ex-o}, \tag{1}$$

$$H_{ex} = \hbar\omega_{ex}S^z, \tag{2}$$

$$H_n = \hbar\omega_n b^+ b, \tag{3}$$

$$H_{ex-n} = \hbar\omega_n \beta S^z (b^+ + b), \tag{4}$$

$$H_{ex-o} = -\mu(S^+ E_p e^{-i\omega_p t} + S^- E_p^* e^{i\omega_p t}) - \mu(S^+ E_s e^{-i\omega_s t} + S^- E_s^* e^{i\omega_s t}), \tag{5}$$

where H_{ex-n} is the interaction between nanomechanical resonator and exciton [31, 33], β is the coupling strength between quantum dot and NR, which has a realistic parameter for $\beta = 0.06$[31]. H_{ex-o} describes the exciton coupling to the two optical fields, E_p and E_s are slowly varying envelope of the pump field and signal field, respectively, μ is the electric dipole moment of the exciton. When the quantum dot couples with the nanomechanical resonator via the coupling strength β, the two-level exciton will be dressed by an infinite number of possible phonon states, as shown in Fig.1(b). Since the ratio of the number of phonons in their $(n+1)$th quantum state to the number in the nth quantum state is $N_{n+1}/N_n = exp\{-\hbar\omega_n/k_BT\}$ at finite temperature T (here k_B is Boltzmann constant), so at low temperature the phonon population in the (n+1)th quantum state is much smaller than that in the nth quantum state. Therefore, as compared with the transition from $|g,n\rangle$ to $|e,n\rangle$, the transition from $|g,n+1\rangle$ to $|e,n+1\rangle$ can be neglected when the system is illuminated by the weak signal beam. In this case, we can only select $|g,0\rangle$, $|e,0\rangle$ and $|g,1\rangle$ as a three-level system shown in Fig.1 (c). The transition from $|g,0\rangle$ to $|e,0\rangle$ just corresponds to the zero-phonon line [34]. All the metastable states other than $|g,1\rangle$ are not considered, because here the transition energy of $|g,0\rangle \rightarrow |e,0\rangle$ (on the magnitude order of $10^{15}Hz$) is much larger than that in $|g,0\rangle \rightarrow |g,1\rangle$ (on the magnitude order of $10^{12}Hz$).

The mechanism of quantum memory by adiabatic passage is well known when the medium is made of lambda three-state atoms. The storage is then achieved through the coherence of the atomic ground states. The idea of present work is to replace the lambda atoms by a two-level quantum dot dressed by the nanomechanical resonator as done in [31] and to take advantage of the long coherence induced by the resonator. In order to investigate the propagation properties of the quantum signal pulse in this NR-QD system, we follow the treatment outlined in [35, 36] and use a quasi-one-dimensional model, consisting of one propagating beam $\hat{\varepsilon}(z,t)$ passing through a medium of length L. $\hat{\varepsilon}(z,t)$ is a weak signal field that couples the ground state $|g,0\rangle$ and first excited state $|e,0\rangle$, and is related to the positive frequency part of the electric field by

$$\hat{E}_s^+(z,t) = \sqrt{\frac{\hbar\omega_{ex}}{2\varepsilon_0 V}}\hat{\varepsilon}(z,t)e^{i(\omega_{ex}/c)(z-ct)}, \tag{6}$$

where ω_{ex} is the frequency of the $|e,0\rangle \rightarrow |g,0\rangle$ transition (i.e.the frequency of exciton), V is the quantization volume of the electromagnetic field, ε_0 is the free space permittivity, z is the direction along the medium of length L. As compared with the three-level atomic systems, here the $|e,0\rangle \rightarrow |g,1\rangle$ transition is driven by the strong pump laser. One can change the pump detuning simply by a tunable pump laser.

To perform a quantum analysis of the light-NR-QD interaction, it is useful to introduce locally averaged operators. Since the thickness of nanomechanical resonator and quantum dot are 30nm [31] and 0.9nm [37] respectively, there may be 30 layers quantum dots embedded in the center of nanomechanical resonator. The area density of InAs/GaAs quantum dots is about $4\times10^{10}cm^{-2}$[38]. So the total number of quantum dots in nanomechanical resonator along with z direction is about $N_z = 10^4 >> 1$. Assuming the slowly-varying amplitude $\hat{\varepsilon}(z_j,t)$ does not change much, we can introduce the locally-averaged, slowly-varying operators

$$\hat{\sigma}_{\mu\nu}(z_j,t) = \frac{1}{N_{z_j}}\sum_{z_j\in N_z}\hat{\sigma}^j_{\mu\nu}(t)e^{i(\omega_{\mu\nu}/c)(z_j-ct)}, \tag{7}$$

where $\hat{\sigma}^j_{\mu\nu}(t) = |\mu^j(t)\rangle\langle\nu^j(t)|$ is the jth QD ($\mu,\nu = g,e,p$).

Going to the continuum limit, the effective interaction Hamiltonian for the reduced three-level system can be written in terms of the locally-averaged operators as[39]

$$\hat{H} = -\int\frac{N\hbar}{L}[g\hat{\sigma}_{eg}(z,t)\hat{\varepsilon}(z,t) + \Omega_p\hat{\sigma}_{ep}(z,t) + \mathrm{H.c.}]dz, \tag{8}$$

where we have assumed that many quantum dots couple to a single nanomechanical resonator [27], so here N is the number density of the QD. $g = \mu\sqrt{\omega_{ex}/2\varepsilon_0 V\hbar}$ is the exciton-quantum signal field coupling constant. $\Omega_p =< 1, g|\ \mu_{ep}\ \mathbf{E(t)}\ |e, 0 > /2\hbar$ describes the coupling to the pump field and the transition, $\mathbf{E(t)}$ is the amplitude of the pump field, the electric dipole moment μ_{ep} corresponds to the transition between the state $|e, 0>$ and the state $|g, 1>$. Since the transition energy of $|g, 0\rangle \to |e, 0\rangle$ (on the magnitude order of $10^{15}Hz$) is much larger than that in $|g, 0\rangle \to |g, 1\rangle$ (on the magnitude order of $10^{12}Hz$), the dipole moments μ and μ_{ep} are on the same order of $20Debye$[40], which are larger than those in atomic systems. The corresponding Rabi frequencies g and Ω_p are on the magnitude order of 10^9 Hz.

The evolution of the Heisenberg operator corresponding to the quantum signal field can be described in a slowly varying amplitude approximation by the propagation equation

$$(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z})\hat{\varepsilon}(z,t) = igN\hat{\sigma}_{ge}(z,t), \tag{9}$$

where c is the light speed in vacuum. The exciton evolution is governed by a set of Heisenberg-Langevin equations

$$\frac{\partial}{\partial t}\hat{\sigma}_{\mu\nu} = -\gamma_{\mu\nu}\hat{\sigma}_{\mu\nu} + \frac{i}{\hbar}[\hat{H}, \hat{\sigma}_{\mu\nu}] + \hat{F}_{\mu\nu}, \tag{10}$$

where $\gamma_{\mu\nu}$ are the excitonic decay rates and $F_{\mu\nu}$ are δ-correlated Langevin noise operators.

Making the approximation that the quantum signal field intensity is much less than that of pump field and assuming all the excitons are initially in the state $|g, 0\rangle$, we can solve Eq.(10) perturbatively to the first order in $g\hat{\varepsilon}/\Omega_p$ to obtain a pair of two equations

$$\frac{\partial}{\partial t}\hat{\sigma}_{ge} = -\gamma_{ge}\hat{\sigma}_{ge} + ig\hat{\varepsilon} + i\Omega_p\hat{\sigma}_{gp} + \hat{F}_{ge}, \tag{11}$$

$$\frac{\partial}{\partial t}\hat{\sigma}_{gp} = -\gamma_{gp}\hat{\sigma}_{gp} + +i\Omega_p\hat{\sigma}_{ge} + \hat{F}_{gp}, \tag{12}$$

where γ_{ge} and γ_{gp} are the decay rates of $|e, 0\rangle \to |g, 0\rangle$ and $|g, 1\rangle \to |g, 0\rangle$, respectively. In the above equations if we assume a sufficiently slow change of pump laser power and neglect the decay rate γ_{gp} of the exciton, and then[35]

$$\hat{\sigma}_{ge}(z,t) \approx -\frac{i}{\Omega_p}\frac{\partial}{\partial t}\hat{\sigma}_{gp}(z,t), \tag{13}$$

$$\hat{\sigma}_{gp}(z,t) \approx -g\frac{\hat{\varepsilon}(z,t)}{\Omega_p}. \tag{14}$$

By combining with Eq.(9), we can obtain the propagation equation of the quantum light pulse in the NR-QD systems in the perturbative and the adiabatic limit as follows,

$$(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z})\hat{\varepsilon}(z,t) = -\frac{g^2 N}{\Omega_p}\frac{\partial}{\partial t}\frac{\hat{\varepsilon}(z,t)}{\Omega_p}. \tag{15}$$

The group velocity of the signal field is given by

$$v_g = \frac{c}{1 + (Ng^2/\Omega_p^2)}, \tag{16}$$

we can see from the above equation that for finite pump field and the large N, the incident signal field can be slowed down significantly as shown by Li and Zhu[27]. One can obtain an analytical solution of Eq.(15) by introducing a new quantum field operator $\hat{\Psi}(z,t)$,

$$\hat{\Psi}(z,t) = \cos\theta(t)\hat{\varepsilon}(z,t) - \sin\theta(t)\sqrt{N}\hat{\sigma}_{gp}(z,t) \tag{17}$$

with

$$\cos\theta(t) = \frac{\Omega_p(t)}{\sqrt{\Omega_p^2(t)+g^2N}}, \tag{18}$$

$$\sin\theta(t) = \frac{g\sqrt{N}}{\sqrt{\Omega_p^2(t)+g^2N}}, \tag{19}$$

$$\tan^2\theta(t) = \frac{g^2N}{\Omega_p^2(t)}. \tag{20}$$

Introducing the adiabaticity parameter $\varepsilon \equiv (g\sqrt{N}T)^{-1}$ with T being a characteristic time, one can expand the equations of motion in power of ε. In lowest order, such as the adiabatic limit, we can obtain[35]

$$\hat{\varepsilon}(z,t) = \cos\theta(t)\hat{\Psi}(z,t), \tag{21}$$

$$\sqrt{N}\hat{\sigma}_{gp} = -\sin\theta(t)\hat{\Psi}(z,t)e^{-i\Delta kz}. \tag{22}$$

Furthermore, the new operator $\hat{\Psi}(z,t)$ obeys the following equation of motion

$$[\frac{\partial}{\partial t} + c\cos^2\theta(t)\frac{\partial}{\partial z}]\hat{\Psi}(z,t) = 0, \tag{23}$$

which describes a shape-preserving propagation with velocity $v = v_g(t) = c\cos^2\theta(t)$. It is should be noted here that $\hat{\sigma}_{gp}(z,t)$ in Eq.(17) and Eq.(22) corresponds to the creation operator of the $|g,0\rangle \to |g,1\rangle$, which is different from atomic spin operator as in three-level atomic systems[39]. In the linear limit, this new operator satisfies the Bosonic commutation relation and we can refer this new Bosonic particle to mechanically induced exciton polariton.

3. Results and Discussions

Equation (23) illustrates a shape- and quantum-state preserving propagation

$$\hat{\Psi}(z,t) = \hat{\Psi}(z,t)(z - c\int_0^t d\tau\cos^2\theta(\tau), 0) \tag{24}$$

It is obvious that by adiabatically rotating θ from 0 to $\pi/2$ via a tunable pump laser, one can decelerate and stop the signal pulse. When $\theta \to 0$, $\Omega^2 \gg g^2N$, which corresponds to the strong external drive field, the polariton has purely photonic character $\hat{\Psi}(z,t) = \hat{\varepsilon}(z,t)$ and the signal propagation velocity equals to the vacuum speed of light. For $\theta \to \pi/2$, the polariton becomes exciton like, $\hat{\Psi}(z,t) = -\sqrt{N}\hat{\sigma_{gp}}e^{i\Delta kz}$, and its propagation velocity approaches zero. In this process, the quantum signal field are mapped onto mechanically induced excitons which are different from the atomic spins in three-level atomic systems. The mechanically

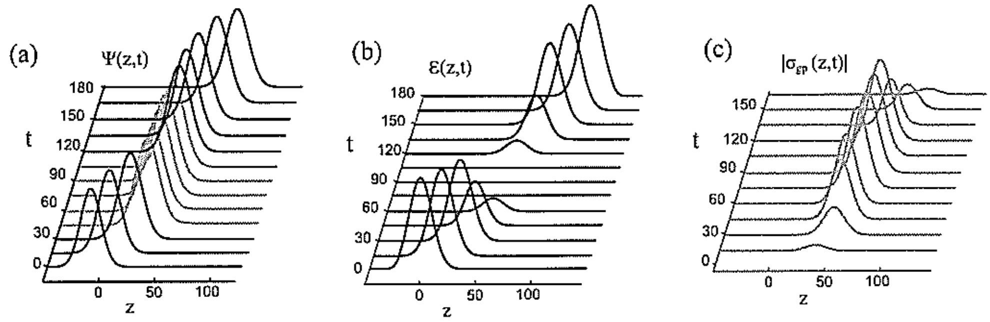

Fig. 2. Quantum light propagation of a dark-state polariton with envelope $exp\{-(z/10)^2\}$, according to the expression $\cot\theta(t) = 100(1-0.5\tanh[0.1(t-15)]+0.5tanh[0.1(t-125)])$.(a) The coherent amplitude of the polariton $\hat{\Psi}(z.t) =< \hat{\Psi}(z,t) >$ as functions of time t and length z. (b)The process of light storage. $\varepsilon(z,t) =< \hat{\varepsilon}(z,t) >$. (c)The matter component part $| \sigma_{gp} |=|< \hat{\sigma_{gp}} >|$,where c=1.

induced exciton polariton can then be reaccelerated to the vacuum speed of light in which the stored quantum states are transferred back to the photonic state. This is illustrated in Fig.2, where displays the coherent amplitude of a dark-state polariton, which results from an initial light pulse, as well as the corresponding field and matter components.

Here, we show an example of the signal laser storage and recall on demand. When the pump laser is switched off, the signal laser information is stored in the coherence between the $|g,0\rangle$ and $|g,1\rangle$ subbands. Turning on the pump laser results in a retrieved signal pulse. There is no additional distortion during the storage because the width of the signal pulse spectrum is very much less than the width of the MICPO window[27].

As we know, when storing light in atomic systems using EIT, characteristics of the field are recorded as a spin wave in the atomic ensemble. The storage time is determined by the coherence times of the hyperfine transitions. However, in our NR-QD systems, the term "*storage*" implies the conversion of signal pulse into the electronic coherence σ_{gp}, whose lifetime is determined by the lifetime of nanomechanical resonator. Towards the realistic NR-QD systems, Verbridge *et al.*[41] recently experimentally showed that for a doubly clamped silicon nitride nanomechanical resonator, the radiative lifetime of resonator can be reached from $0.8\mu s$ to $0.1s$ via different tensile stress. Consequently, this means the light storage time can reach a ideal situation if we select a long vibration lifetime of NR. Therefore, the NR-QD system we proposed here is a suitable choice for light storage and retrieval.

4. Conclusions

In conclusion, we have theoretically achieved the quantum light memory by tuning another pump laser in a coupled nanomechanical resonator-quantum dot system. It is shown that it is possible to store and retrieve the signal light by switching off and on the pump laser. This light storage is based on the mechanically induced exciton polaritons consisting of quantum light and mechanically induced dressed exciton. For this light memory device, the storage time of signal pulse can be determined by the vibration lifetime of nanomechanical resonator. Taking advantages of this optical device, it has prepared the stage of all optical buffers, quantum optical processing and other related biological[42], chemical applications[43]. Finally, we hope that our predictions in the present work can be testified by experiment in the near future.

Acknowledgement

The part of this work was supported by National Natural Science Foundation of China (No.10774101 and No.10974133) and the National Ministry of Education Program for Ph.D.

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