Strongly confined light in a singe mode near quantum dots embedded in photonic crystals

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Abstract- The strong confinement of light composed of a single localized mode inside photonic crystals can be achieved by coherent control, which is useful for keeping and processing quantum information.

I. INTRODUCTION

The confinement of light near a very small defect embedded inside photonic crystals with a photonic band gap (PBG) is expected to be the basis of achieving micro- and nano-photonic crystal devices [1]. Such light confinement has been experimentally achieved by combing 3D photonic crystals and surface 2D PBG structures [2]. This phenomenon of light confinement is accompanied by an anomalously large vacuum Rabi splitting. The Rabi splitting causes the formation of several localized modes in confined light [3]. An increasing motivation is to form confined light composed of a single localized mode to achieve photonic crystal devices, such as optical logic gates including quantum logic gates. One approach is the band gap control method using a tunable PBG [4], where the creation and elimination of specific localized modes in confined light is controlled by opening and closing the PBG, to create a single-mode confined light. However, this results in a large loss of the energy of confined light. Recently, we have proposed the coherent control using a dark line (a spectrum singularity leading to the complete quenching of emission at certain values of emitted photon frequencies), where confined light can be controlled without closing the PBG [5,6].

In this paper, we demonstrate that light is confined in a singe mode near a quantum dot embedded in photonic crystals by coherent control using a dark line. Here, we clarify the strong confinement and a very fast response time, compared to the tunable PBG method. This is useful for keeping the memory in a two-state quantum system such as a qubit and for processing quantum information.

II. QUANTUM DOT IN PHOTONIC CRYSTALS

A quantum dot embedded in 3D photonic crystals is assumed to be an ideal quantum system with an atomic-like energy configuration composed of two upper levels (|3> and |2>) and a ground level (|1>). At the initial time t=0, the quantum dot is assumed to be excited to form a coherent superposition of the two upper levels, using a pump laser pulse with a phase ϕ and an area θ, as

$$|\psi(0)\rangle = \cos(\theta/2)|2\rangle + e^{i\phi}\sin(\theta/2)|3\rangle . \tag{1}$$

Such a state vector composed of a two-state system can be graphically represented by a point on the Bloch sphere, as shown in Fig. 1. This two-state system can act as an optical memory to encode quantum information, such as a qubit.

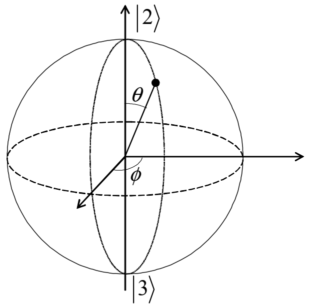

Fig. 1. Bloch sphere representation.

To keep the memory in the state vector $|\psi(t)\rangle$ for t>0, it is necessary to maintain highly excited states, which may be guaranteed by the formation of a photon-atom bound state, where the emitted photon remains partially localized in the vicinity of the emitting atom, due to the presence of a PBG [3,5,6]. Therefore, we assume that one of the transition frequencies of the quantum dot is far inside the PBG so that the spontaneous emission is completely forbidden. The other transition frequency is assumed to be near (but inside) the PBG to coherent control, where the two upper levels are coupled by a laser field. This model can describe the essential physics of the optical properties of photonic crystals and may enable the realization of experimental systems such as an ensemble of CdSe-ZnSe quantum dots embedded in an inverse opal consisting of air spheres in TiO_2 [3].

III. TIME EVOLUTION OF STATE VECTOR

Figure 2 shows the time evolution of the state vector $|\psi(t)\rangle$ in the Bloch sphere representation, according to the Schrödinger equation considering the above photonic crystal environment. At the initial time (t=0), the quantum dot is fully excited, so that the norm of the state vector $|\psi(0)\rangle$ is $R(0)$=1. In the course of a short time on the order of picoseconds (one or two rotations on the Bloch sphere), the excited state partially decays to the ground state, so that the norm R(t) is reduced to 0.85. However, after that, due to the light confinement effect, the quantum dot remains the excited state with $R(t)=0.85$, whose state vector widely rotates inside the Bloch sphere. This rotation comes from the quantum interference between several localized modes in confined light, which are caused by the Rabi splitting.

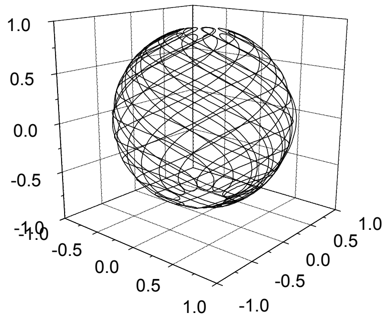

Fig. 2. Time evolution of the state vector.

Figure 3 shows the time evolution of the state vector $|\psi(t)\rangle$ in the formation process of single-mode confined light, where, using the tunable PBG method, the PBG is partially closed to remain only one localized mode in confined light. In this case, for several tens of picoseconds from $t=0$, the state vector $|\psi(t)\rangle$ exhibits the random rotations inside the Bloch sphere. This shows the release of the localized modes that are moved out of the PBG, where these modes travel away from the photonic crystals in the form of a traveling pulse. After that, steady single-mode confined light is formed, and the state vector $|\psi(t)\rangle$ exhibits circular rotations with a single frequency oscillation inside the Bloch sphere; however, the norm $R(t)$ is largely reduced to 0.45, due to the energy loss of confined light that travel away from the photonic crystals.

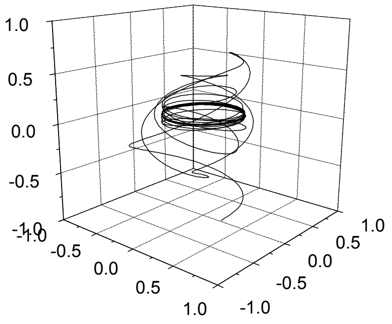

Fig. 3. Time evolution of the state vector in the formation process of single-mode confined light using the tunable PBG method.

The curve C1 in Fig. 4 shows the same formation process of single-mode confined light as Fig. 3, but here we consider the coherent control method using the dark line. In this case, to remain only one localized mode, the other modes are eliminated by tuning to the dark line (that is a spectrum singularity leading to the complete quenching of emission).[5, 6] An important feature of this method is that confined light is controlled without closing the PBG. Comparing C1 and Fig. 3, C1 immediately exhibits circular rotations with a single frequency oscillation in a very short time from $t=0$. This is because, in this method, the elimination of the localized modes comes from the energy transfer in the confined light, which is accompanied by a very fast response time. The curve C2 shows the case of Fig. 3 in a long time limit. P1 and P2 are the projections on the x-y plane of C1 and C2, respectively. Comparing P1 and P2, we find that the radius of P1 is sufficient large and the norm $R(t)$ of C1 remains 0.85. This is because, in the coherent control method, the PBG is not closed, so that confined light remains localized near the quantum dot, even in the control of confined light. Such a highly excited state with a single frequency oscillation and a very fast response time on the picosecond time scale are useful for keeping the memory in the two-state quantum system and for processing quantum information in a qubit, leading to a quantum logic gate.

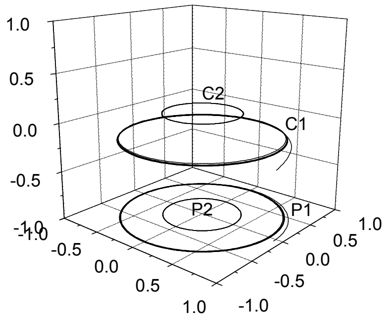

Fig. 4. Time evolution of the state vector in the formation process of single-mode confined light using the coherent control method.

IV. CONCLUTION

We have theoretically demonstrated the formation of single-mode confined light inside photonic crystals, using the coherent control method. Confined light is controlled without closing the PBG, so that the energy loss of confined light is strongly suppressed. Furthermore, its response time on the picosecond time scale is very fast. Such low-loss and high-speed control for a two-state quantum mechanical system is useful for various applications such as a qubit and quantum logic gates.

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