Quantum optical effect for switching and slow light applications

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Abstract. *In this paper, the modeling of optically tunable all-optical switching and slow-light device is addressed. We consider cavity-based add-drop and direct-coupled filters as switching elements, and analyze the static and dynamic behaviours; for tunable delay lines, we investigate coupled-resonator optical waveguide (CROW) structures. The tunability of the system under investigation is discussed considering the joint interference effect created by a not excited dipole in a cavity in Purcell regime, and the interference effect in a quantum state by Electromagnetic Induced Transparency (EIT).*

Introduction

One of the main tasks for applications of nanotechnology in Data&Telecom market is the development of innovative devices like lasers with low threshold current, nanocavity laser arrays, add-drop filters for wavelength routing networks, buffers for Optical Burst Switching (OBS) and Optical Packet Switching (OPS) and quantum information devices [1]. The progress in fabrication of 2D Photonic Crystal (PhC) cavity-based structures, achieving recently Q parameters of order of millions [2], gives the opportunity to obtain strong light matter interaction in a small volume V. In particular, by increasing the Purcell factor Q/V, we can design a quantum-based device, and by tuning the decay rate of a dipole through the electromagnetic environment, we can exploit the interaction between a cavity mode and a quantum state [3]. In this paper, we refer to PhC and Quantum Dot technology, and we consider a single quantum dot inside a PhC cavity, analyzing the behavior of side- and direct-coupled waveguides for switching purpose; then we analyze a Coupled Resonator Optical Waveguides (CROW) as a slow light device.

Switching device

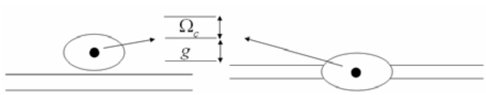


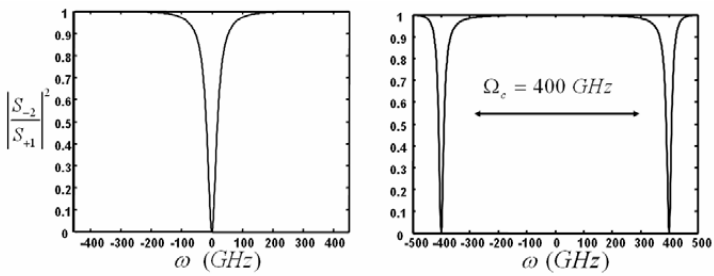
Figure 1: Side and directed coupled PhC cavities

We consider the device of Figure 1, and we suppose that there is a quantum state inside the cavity, composed of three energy levels where one of the two transitions is entangled to a cavity mode through the g parameter [4, 5]. The other transition is driven by a coherent field, not related to any cavity mode, that is described by the Rabi frequency Ω_c. We suppose to work in Purcell regime [6], i.e. the Purcell factor is larger than one

$$F_p = \frac{g^2}{\gamma'\left(\frac{1}{\tau_0}+\frac{1}{\tau_{e1}}+\frac{1}{\tau_{e2}}\right)} \gg 1$$

but there is not strong coupling between the cavity mode and the quantum state. This condition is satisfied for high values of the g parameter, but also if the dipole decay rate γ' is much smaller than the whole decay rate of the cavity, that is related to τ_0, τ_{e1} and τ_{e2}. This situation can be achieved by a suitable design of the cavity, considering the Spontaneous Emission (SE) rate of the dipole in the cavity and by a proper alignment between the cavity mode and the dipole moment matrix elements of the quantum state, but also by reducing the volume of the cavity mode to increase the g parameter [5].

In Figure 2, the power spectral density of the direct-coupled system is shown in two cases: when the pump signal is switched off (Ω_c=0), we observe a sharp transmittance peek and for Ω_c=400 GHz, the so called Rabi splitting is achieved in the quantum state, and the distance between the two symmetric transitions is $2\Omega_c$.



(a) (b)

Figure 2: Power spectral density of a direct-coupled cavity: (a) $\Omega_c = 0$ (b) $\Omega_c = 400$ GHz

This behavior is similar to that one in a EIT material, where a coherent field cancels the absorption of a probe transition, if the two allowed transitions share a common energy level. In side-coupled system, we have an opposite behavior and the signal is reflected or dropped, depending on the design, when the pump is on [4]. This effect holds in a weak excitation limit, when the photon flux is much smaller than the Purcell factor [3, 7].

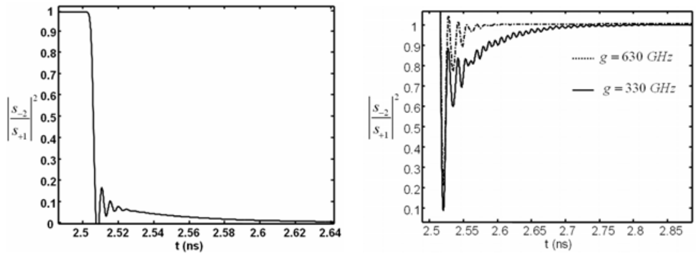
We have performed our analysis in both frequency and time domains, and the transient behavior of the side- and direct-coupled systems are shown in Figure 4, for two values of the g parameter. We have considered an input monochromatic field, and it is evident that a large Purcell factors speeds the creation of the dark state in an EIT material; we also observe that a side-coupled system has a larger Q parameter.

Slow-light device

The proposed approach can be used to design a tunable slow-light device based on a CROW. We assume that the whole Hamiltonian of the system is

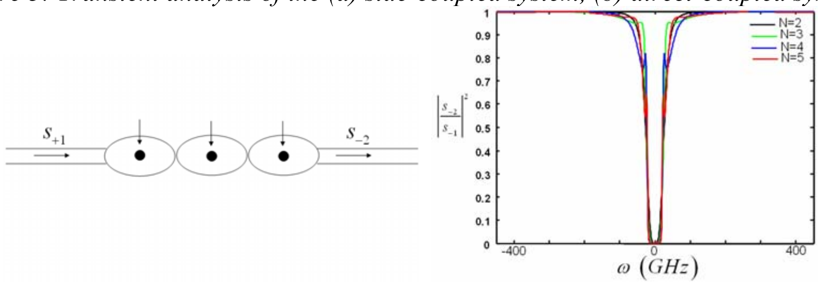
$$H=\sum_R\left(E_1^R|1\rangle\langle 1|+E_2^R|2\rangle\langle 2|+E_3^R|3\rangle\langle 3|\right)+\sum_R\hbar\omega_p a_R a_R^\dagger+\kappa\sum_{R,R'}(a_R a_{R'}+h.c.)-\sum_R\hbar g\left(\sigma_+^R a_R+\sigma_-^R a_R^\dagger\right)-$$

where the first term is the energy level related to the quantum state in each cavity, the second term is related to photon number of the mode in each cavity, the third term is related to photon hopping between neighbor cavities, and the forth and the fifth terms are related to the interaction part in the rotating wave approximation, between each cavity mode and the quantum state inside. The last two terms are related to the modes in the waveguides that are coupled to the first and the last cavity [6]; κ, κ' are the coupling coefficients between neighbor cavities that can be calculated through an overlap integral [7].



(a) (b)

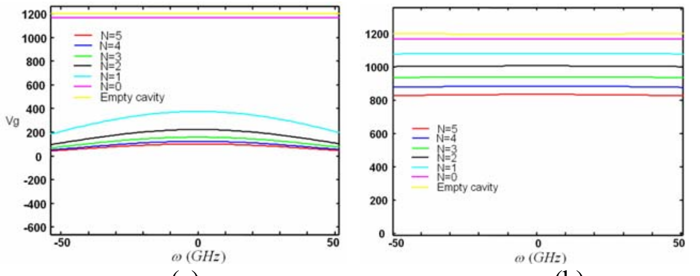
Figure 3: Transient analysis of the (a) side-coupled system, (b) direct-coupled system.



(a) (b)

Figure 4:(a) CROW system under investigation (b) Reflectivity considering $\Omega_c^j = 0$ *(in the j-th cavity)*

We consider an interaction picture, to eliminate the time dependence of the pump signals, and derive the Heisenberg picture of the system. In Figure 4b the transmittance considering different numbers of cavities N with a resonant dipole is shown, and we observe that the reflectivity bandwidth increases, and the frequency response becomes more flat, by increasing the number of cavities. Figure 5 shows the group velocity, and we observe that the slowing down effect is larger for a small value of the Rabi frequency of the pump, in accordance with the dispersion relation of an EIT material.
N is the number of cavities with a value of the pump signal of 100 GHz in Figure 5 (a) or 500 GHz in Figure 5 (b), and all the remaining cavities have a 2THz pump, that is quite identical to have no pump effect.



(a) (b)

Figure 5: Group velocity for (a) $\Omega_c^j = 100$ *GHz (b)* $\Omega_c^j = 500GHz$ *(in the j-th cavity)*

We observe that for N=5 we obtain the maximum group velocity reduction in both case, as expected, and that there are two different behaviours in the two cases. For Ω_c=500 GHz, the light speed reduction varies linearly with N (the curves are equally spaced apart), and it is almost constant over the frequency bandwidth, whereas this is not true for Ω_c=100 GHz.

Conclusions

In this paper, we have analyzed the behavior of different PhC and Quantum Dot system for switching and slow light applications, in the Purcell regime. We have investigated different regimes of EIT material in microcavities [10] to drop or slow down an input monochromatic signal. The EIT effect created in a single quantum dot has been considered, in both static and transient regimes; a CROW device is investigated as an optically tunable buffer, with a large bandwidth.

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