Capturing light pulses into a pair of coupled photonic crystal cavities

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We describe finite-difference time-domain simulations of a two-dimensional photonic crystal implementation of a two-resonator system capable of capturing light pulses from a waveguide. As much as 99.61% of incident pulse energy is captured in simulations. The release of near-perfect Gaussian pulses is also demonstrated. © *2009 American Institute of Physics*.
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Stopping light in technologically relevant systems, such as photonic crystals, has important implications for various optical information processing tasks, including buffering and nonlinear signal processing.[1,2] The initial theoretical proposal for such a system requires tuning many resonators[3] and has not yet been implemented. Recent experimental studies instead used either one or two dynamically tuned resonators, and have demonstrated partial capture of pulses.[4–6] In a previous paper, using coupled mode theory, we have proposed a general theoretical condition for completely capturing pulses with the use of several cavities.[7] Related work on pulse capturing in atomic media with small optical depth has been considered in Ref. 8.

In this letter we numerically implement the condition described in Ref. 7 by simulating a two-dimensional photonic crystal system as shown in Fig. 1(a) using finite-difference time-domain (FDTD) methods. Our simulation indeed demonstrates near-complete pulse capture. The simulations have also provided a validation of the coupled mode theory model shown in Fig. 1(b).

We start by using this coupled mode theory model to highlight the essential physics of pulse capture and release in a few dynamically tuned cavities. For this system, the coupled mode theory equations are

$$\frac{da_1}{dt} = i\omega_1 a_1 + i\beta a_2 - \frac{\gamma_1}{2}(\gamma_1 a_1 + \gamma_2 a_2) + \gamma_1 a_{wg}^+,$$

$$\frac{da_2}{dt} = i\omega_2 a_2 + i\beta a_1 - \frac{\gamma_2}{2}(\gamma_1 a_1 + \gamma_2 a_2) + \gamma_2 a_{wg}^+,$$

$$a_{wg}^- = -a_{wg}^+ + (\gamma_1 a_1 + \gamma_2 a_2), \tag{1}$$

where a_1 and a_2 are the complex field amplitudes in the cavities, a_{wg}^+ and a_{wg}^- are the incoming and outgoing wave amplitudes inside the waveguide, β is the direct coupling strength due to modal overlap between the cavity modes, and γ_1 and γ_2 are the coupling strength between each of the two cavity modes and the waveguide.[9] Notice that such a waveguide-cavity coupling also induces an indirect coupling between the cavities.

The key to pulse capture and release lies in the presence of a dark state in this system. When $\omega_1=\omega_2=\omega_0$ and $\gamma_1=\gamma_2$, one of the eigenstates of the system, with $a_1=-a_2$, which has an eigenfrequency $\omega_0-\beta$, does not leak into the waveguide. Suppose the system is initially in such a dark state. Then by dynamically detuning the two resonances such that $\omega_1 \neq \omega_2$, the energy in the cavities leaks into the waveguide, generating a released pulse. Conversely, since the underlying physics is time-reversal invariant, the time-reversed temporal detuning trajectory allows for the complete capture of the time-reversed pulse into the dark state.

We implement the system of Eq. (1) numerically by simulating the structure shown in Fig. 1(a). The structure consists of a triangular lattice of air holes ($r=0.275a$, where a is the lattice constant.) in a dielectric. The dielectric is silicon ($\varepsilon=11.56$), and for our two-dimensional simulations we used an effective $\varepsilon=8.94$ appropriate for a slab with a thickness of $0.829a$.[10] In the simulations, 15 grid points were used per lattice constant. The cavities are formed by removing three holes. The waveguide is formed by removing one row of holes. Also, the radius of the holes adjacent to the waveguide is shrunk to $r=0.24a$, so that the band edge of the waveguide is moved away from the cavity resonances, allowing for design of a perfectly matched layer with low reflection (0.66%).[11]

In the absence of modulation, this system can be described with static values for the parameters, i.e., $\gamma_1=\gamma_2$

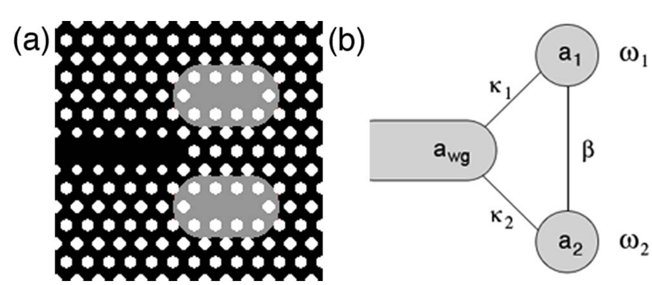

FIG. 1. (Color online) (a) A part of the implementation of the pulse capture/release structure in a two-dimensional photonic crystal. The black is dielectric ($\varepsilon=8.94$), the gray is modulated dielectric, and the white is air ($\varepsilon=1$). (b) A coupled mode theory model of the structure. On the left is a waveguide, and on the right are resonators, represented by circles. The cavities are coupled to the waveguide with coupling constants γ_1 and γ_2, and directly coupled to each other with coupling constant β.

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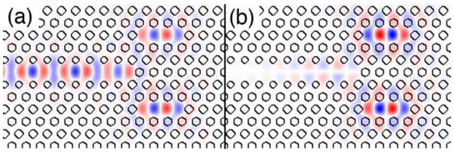

FIG. 2. (Color online) The H_z field at (a) $t=0.3$ T and (b) $t=7.1$ T.

$=\gamma_0$, $\beta=\beta_0$, and $\omega_1=\omega_2=\omega_0$. We calculate these parameters by first directly exciting the cavity modes in FDTD simulations. We then determine the decay rate, resonant frequency, and relative amplitude of the eigenmodes of the system by performing a harmonic inversion of the decaying cavity field amplitudes.[12] From this information we obtain the coupled mode theory parameters in Eq. (1). The calculated values are $\gamma_0^2=2.924\times10^{-3}(c/a)$, $\beta_0=1.210\gamma_0^2$, and $\omega_0=0.2473(2\pi c/a)$.

As a demonstration, we will use dynamic modulation to capture an incident unchirped Gaussian pulse of the form

$$a_{wg}^{+}=Ae^{-(t-4T)^2/2T^2}\cos(\omega_p t+\varphi). \quad (2)$$

The method we develop is general, though, and can be applied to other pulse forms as well. We choose $\omega_p=\omega_0-\beta_0$, so that the pulse frequency matches the eigenfrequency of the dark state. We choose $\gamma_0^2 T=10.33$. We generate this pulse by exciting a point current source in-plane and perpendicular to the waveguide, located in the center of the waveguide at a distance $30a$ from the cavities.

As the pulse approaches the cavities, the resonant frequencies of the cavities are tuned by dynamically changing the dielectric constant by the amounts $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ in the regions within a distance $1.25a$ around each cavity. Figure 2 shows snapshots of the out of plane H_z field during and after this dynamic process. The final state corresponds to the dark state of the system.

The tuning trajectories $\Delta\varepsilon_j(t)$ are determined by combining coupled mode theory with FDTD simulations on *static* systems. The procedure is as follows. We first calculate $\Delta\omega_i=\omega_i-\omega_0$ from coupled mode theory by numerically integrating Eq. (1) in a pulse release scenario, where energy is initially stored in the dark state, and $a_{wg}^{+}=0$. We partition the period of integration into many small time intervals. Within each interval, we vary $\Delta\omega_i(t)$ until the pulse released from the cavity matches with the desired pulse form of Eq. (2) in the same interval. For the pulse of Eq. (2), since it is unchirped, we enforce the condition $|a_2|\Delta\omega_2=-|a_1|\Delta\omega_1$, so that the instantaneous frequency of the released pulse is kept approximately fixed. As discussed above, the pulse capture tuning curve is the time reverse of the pulse release curve. To determine $\Delta\epsilon_j$ from $\Delta\omega_i$, we simulate structures with various dielectric modulations, and perform the same parameter extraction procedure as outlined above.

The generated $\Delta\varepsilon_i(t)$ is shown in Fig. 3(a). The use of such modulation results in capturing of pulse with near-unity efficiency. We determine the capture efficiency based on flux measurements. The flux is measured through a vertical line halfway between the source and the cavities, and integrated in time to yield the total energy E_T transferred from the source to the cavities. To calculate a capture efficiency, we find the total energy in the pulse E_P by measuring the time-integrated flux of an identically excited pulse through an unimpeded waveguide with no termination or cavities. The final result is a capture efficiency $E_T/E_P=99.61\%$.

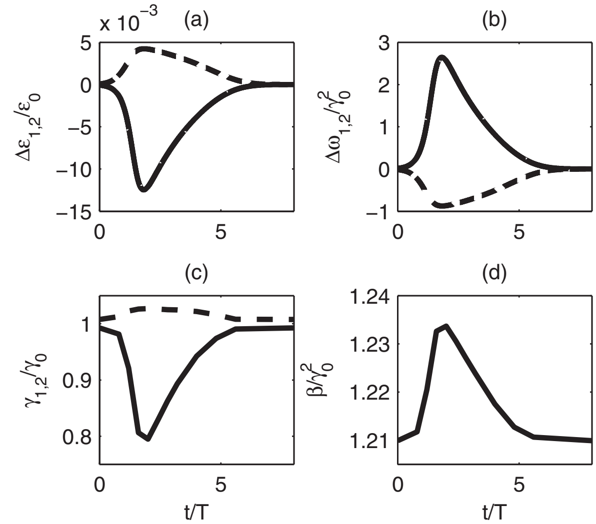

FIG. 3. The parameters used in the simulations as a function of time. (a) The dielectric modulation curves for the two cavities, used in FDTD simulations. ε_0 is the dielectric constant in the absence of modulation, not the value in vacuum. (b) The resulting resonant frequency detuning, used in coupled mode simulations. (c) The coupling rate of the two cavities to the waveguide. (d) The intercavity coupling rate.

For the purpose of generating the temporal trajectory of the tuning, we use time-independent parameter values $\gamma_1=\gamma_2=\gamma_0$ and $\beta=\beta_0$ in the coupled mode equations. The data extraction procedure, however, has indicated a dependency of these coupling constants on $\Delta\varepsilon_j$ [as shown in Figs. 3(b)–3(d)] and hence a temporal dependency of these parameters. Taking this temporal dependence into account, we numerically integrated the coupled mode Eq. (1) and compared to FDTD simulations. Figure 4(a) shows excellent agreement between the predicted (coupled mode theory) and measured (FDTD) total energy in the two cavities as a function of time. The coupled mode theory predicts a capture efficiency of 99.63%, which agrees well with the measured FDTD value. In comparison, if the temporal dependency in coupling rates is not taken into account, the predicted capture efficiency is 99.98%.

Once energy is stored in the cavities, the time-reversed detuning curve should result in the release of a Gaussian pulse. Figure 4(b) shows the predicted and measured field amplitude in the waveguide as a function of time for a pulse release simulation. The amplitude of the released pulse deviates from the predicted amplitude by less than 2% of the maximum amplitude during the process.

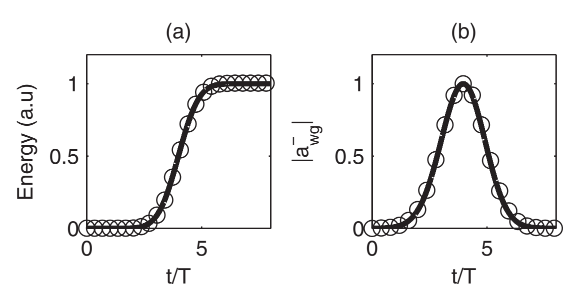

FIG. 4. Comparison of coupled mode theory and FDTD simulation results. (a) The energy in the two cavities in a pulse capture simulation. The black curve is the FDTD result and the circles are the coupled mode theory prediction. (b) The pulse amplitude in a pulse release simulation. The black curve is the FDTD result and the circles are the coupled mode theory prediction.

The system parameters we chose were based on computational considerations rather than physical implementation issues. With a lattice constant $a=370$ nm, the parameters correspond to a carrier frequency of 200 THz and a pulse width of $T=4$ ps. Longer pulse widths, which are more amenable to practical implementation with available index of refraction modulation rates,[13,14] may be obtained by increasing $\gamma_0^2 T$.[7]

This scheme requires that the two cavities have very close resonant frequencies. The presence of fabrication imperfections typically leads to cavities with substantial frequency splitting. Nevertheless, a recent work has overcome this problem through the use of differential thermal tuning.[10] The scheme also requires independent tuning of the two cavities. For this purpose we note that the carrier diffusion length in etched Si is in the submicron scale,[15] shorter than the typical distance between the cavities. Finally, in the presence of intrinsic cavity loss, while the tuning needs to occur within a time scale shorter than the cavity lifetime, there always exists a tuning scheme that results in negligible reflection, and which maximizes the amount of energy captured.[7]

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