Stopping Light All Optically

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We show that light pulses can be stopped and stored coherently, with an all-optical adiabatic and reversible pulse bandwidth compression process. Such a process overcomes the fundamental bandwidth-delay constraint in optics and can generate arbitrarily small group velocities for any light pulse with a given bandwidth, without any coherent or resonant light-matter interactions. We exhibit this process in optical resonators, where the bandwidth compression is accomplished only by small refractive-index modulations performed at moderate speeds.

The ability to drastically slow down the propagation speed of light, and to coherently stop and store optical pulses, holds the key to the ultimate control of light and has profound implications for optical communications [1] and quantum information processing [2,3]. In order to reduce the group velocity of light coherently, there are two major approaches, employing either electronic or optical resonances. Using electronic resonances in atomic systems, the group velocity of light can be decreased by orders of magnitude [4]. Furthermore, with the use of quantum interference, absorption at some electronic resonances can be suppressed [5]. Dramatic slow down and complete stop of light pulses can be accomplished by converting optical signals into electronic coherences [6–13]. The use of electronic states to coherently store the optical information, however, imposes severe constraints. As a result, only a few very special and delicate electronic resonances available in nature possess the required properties. All the demonstrated bandwidths are far too small to be useful for most purposes. The wavelength ranges where such effects are observed are also very limited. Furthermore, while promising steps were taken for room temperature operation in solid-state systems, it still remains a great challenge to implement such schemes on-chip with integrated optoelectronics [12,13].

Consequently, it is of great interest to pursue the control of light speed using optical resonances in photonic structures including microcavities [14] and photonic crystals (PC) [15–17]. Photonic structures can be defined by lithography and designed to operate at any wavelength range. Ultrahigh quality-factor cavities have been realized on-chip [18], and group velocities as low as $10^{-2}c$ for pulse propagation with negligible distortion have been observed in PC waveguide band edges [19] or with coupled resonator optical waveguides (CROW) [20–22]. Nevertheless, such structures are fundamentally limited by the delay-bandwidth product [23]—the group delay from an optical resonance is inversely proportional to the bandwidth within which the delay occurs. Therefore, for a pulse with a given temporal duration and corresponding bandwidth, the minimum group velocity achievable is

limited. In a CROW waveguide structure, for example, the minimum group velocity that can be accomplished for pulses at 10 Gbit/s rate at $\lambda = 1.55$ μm is no smaller than $10^{-2}c$. For this reason, up to now, photonic structures could not be used to stop light.

Here we introduce a set of general criteria to overcome the fundamental limit due to the delay-bandwidth product. These criteria enable the generation of arbitrarily small group velocities for optical pulses with a given bandwidth, while preserving the coherent information entirely in the optical domain. We show that these criteria can be achieved in optical resonators using only small refractive-index modulations at moderate speeds, even in the presence of losses. Also, since the bandwidth constraints occur in almost all resonant physical systems, our approach has general applicability.

In order to coherently stop a pulse with a given bandwidth, the following criteria must be satisfied.

(a) The system must possess large tunability in its group velocity. To allow for a pulse with a given bandwidth to enter the system, the system must possess an initial state with a sufficiently large bandwidth (i.e., a large group velocity as required by the delay-bandwidth product) in order to accommodate all the spectral components of the pulse. We design a system such that a small refractive-index shift can change the group velocity by an arbitrarily large orders of magnitude and that the group velocity reduction is independent of losses.

(b) The tuning of the system should be such that the bandwidth of the pulse is reversibly compressed. Such bandwidth compression is necessary in order to accommodate the pulse as the system bandwidth is reduced. Thus, the tuning process must occur while the pulse is completely in the system and must be performed in an adiabatic [24] fashion to preserve the coherent information encoded. In our design, we use a translationally invariant refractive-index modulation to conserve the coherent information in each wave-vector component. The modulation accomplishes coherent frequency conversion for all spectral components and reversibly compresses the pulse bandwidth.

We exhibit these concepts in the system shown in Fig. 1, which consists of a periodic array of coupled cavities. Each unit cell of the periodic array contains a waveguide cavity A, which is coupled to the nearest neighbor cells to form a coupled resonator optical waveguide, and one or more side cavities B_1 and B_2, which couple only to the cavities in the same cell. The side cavities in adjacent cells are placed in an alternating geometry in order to prevent coupling between them.

For the simple case where only a single side cavity B exists in each unit cell, the dynamics of the field amplitudes a_n, b_n for cavities A and B in the nth cell can be expressed using coupled mode theory as

$$\frac{da_n}{dt} = i\omega_A a_n + i\alpha(a_{n-1} + a_{n+1}) + i\beta b_n - \gamma_A a_n, \quad (1)$$

$$\frac{db_n}{dt} = i\omega_B b_n + i\beta a_n - \gamma_B b_n. \quad (2)$$

Here α, β are the coupling constants between the pairs of cavities A-A and A-B, respectively. ω_A and ω_B are the resonance frequencies, and γ_A and γ_B are the loss rates for cavities A and B, respectively.

Since the system has translational symmetry along the waveguide, the frequencies $\omega_{\pm,k}$ for the eigenstates of the system can be related to a wave vector k as

$$\omega_{\pm,k} = \frac{1}{2}\{\omega_{A,k} + \omega_B + i(\gamma_A + \gamma_B) \\ \pm \sqrt{[\omega_{A,k} - \omega_B + i(\gamma_A - \gamma_B)]^2 + 4\beta^2}\}, \quad (3)$$

where $\omega_{A,k} = \omega_A + 2\alpha\cos(k\ell)$ represents the frequency band of the waveguide by itself. For concreteness, we focus on the lower band $\omega_{-,k}$, which at the band center has a group velocity v_{g-},
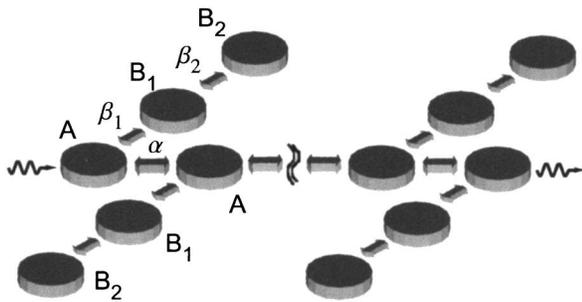

FIG. 1. Schematic of a tunable microcavity system used to stop light. The disks represent cavities, and the arrows indicate available evanescent coupling pathways between the cavities. The system consists of a periodic array of coupled cavities. Each unit cell of the array contains a waveguide cavity A, which couples to nearest neighbor cells via evanescent coupling with a coupling strength α. Each waveguide cavity A is also coupled to either one or more side cavities (with coupling strength β_i). The figure shows the case with two side cavities, labeled B_1 and B_2.

$$\mathrm{Re}\left[\frac{d\omega_{-,k}}{dk}\right]_{k=\pi/2\ell} = \alpha\ell\,\mathrm{Re} \\ \times \left(1 - \frac{\Delta + i(\gamma_A - \gamma_B)}{\sqrt{[\Delta + i(\gamma_A - \gamma_B)]^2 + 4\beta^2}}\right) \quad (4)$$

with $\Delta \equiv \omega_A - \omega_B$. When $\Delta \ll -|\beta|$, the lower band exhibits a large group velocity ($v_{g-} \simeq 2\alpha\ell$) and a large bandwidth [Fig. 2(a)]. When $\Delta \gg |\beta|$ [Fig. 2(b)], the group velocity at the band center (and also the bandwidth) is reduced by a ratio of $\beta^2/\Delta^2 + (\gamma_A - \gamma_B)^3/(4\Delta^3)$. Importantly, the group velocity becomes independent of loss when γ_A and γ_B are equal. Also, by increasing the number of side cavities in each cell (Fig. 1), the achievable minimum group velocity at the band center can be further reduced to $2\alpha\ell\prod_{i=1}^{r}(\beta_i/\Delta)^2$, where r is the number of the side cavities in each cell and β_i is the coupling constant between the $(i-1)$th and ith side cavities as shown in Fig. 1. Thus, the group velocity can be reduced exponentially with a linear increase in system size, and arbitrarily large group velocity tuning can be accomplished with small refractive-index variations that shift the resonant frequencies.

In this system, a pulse can be stopped by the following process: Initially $\Delta \ll -|\beta|$; the lower band has large bandwidth. By placing the center of $\omega_{-,k}$ at the pulse carrier frequency ω_0 [Fig. 2(a)], the lower band can accommodate the entire pulse, with each of its spectral components occupying a unique wave vector. After the pulse is completely in the system, we vary the resonance frequencies until $\Delta \gg |\beta|$ [Fig. 2(b)], at a rate that is slow compared with the frequency separation between the bands. (The frequency separation reaches a minimum of $2|\beta|$ when $\Delta = 0$.) The modulation of the cavity resonances preserves translational symmetry. Therefore, cross talk between wave vector components of the pulse is
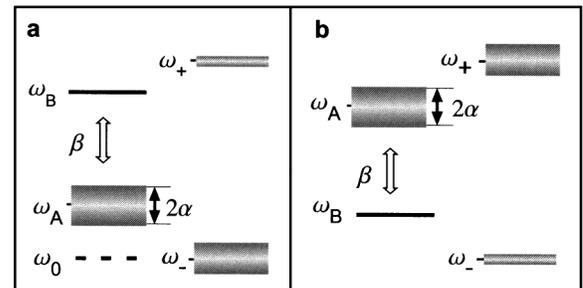

FIG. 2. Schematic of the frequency bands ω_+ and ω_- for the system shown in Fig. 1 with a single side cavity in each unit cell. ω_A and ω_B are the resonance frequencies for the waveguide cavities A and the side cavities B, and β is the coupling constant between them. The widths of the lines represent the widths of the frequency bands. (a) $\omega_A - \omega_B \ll -|\beta|$. The frequency band ω_- exhibits a large bandwidth centered at the pulse frequency ω_0. (b) $\omega_A - \omega_B \gg |\beta|$. The frequency band ω_- exhibits a small bandwidth.

prevented during the tuning process. Also, the slow modulation rate ensures that each wave vector component follows only the lower band, with negligible scattering to the upper band (i.e., the system evolves adiabatically [24]). Consequently, the pulse bandwidth is reversibly compressed via energy exchange with the modulator, with all the information preserved. During the bandwidth compression, the modulation need not follow any particular trajectory in time except being adiabatic and can have a far narrower spectrum than the incident pulse.

We implement this system in a PC with a square lattice of dielectric rods ($n = 3.5$) with a radius of $0.2a$ (a is the lattice constant) in air ($n = 1$) (Fig. 3). The PC possesses a gap for modes with electric field parallel to the rod axis. Decreasing the radius of a rod to $0.1a$ generates a single mode cavity resonant at $\omega_0 = 0.3224(2\pi c/a)$. Two neighboring cavities A and the adjacent cavities A and B couple through barriers of three rods ($\ell = 4a$), with coupling constant $\alpha = \beta = 0.00371(2\pi c/a)$. The resonant frequencies are tuned by refractive-index modulation of the rods. We simulate the entire process of stopping light for 100 cavity pairs with the finite-difference time-domain (FDTD) method, which solves Maxwell's equations without approximation. The waveguide is terminated by introducing in the last cavity a loss rate equal to the coupling constant α, which provides 100% absorption for the waveguide mode. The process for stopping light is shown in Fig. 3(a). We generate a Gaussian pulse by exciting the first cavity. (The process is independent of the pulse shape one chooses.) The excitation reaches its peak at $t = 0.8t_{\text{pass}}$, where t_{pass} is the traversal time of the pulse through the waveguide by itself. While the pulse is generated, the waveguide is in resonance with the pulse, and the side cavities are detuned. The field is concentrated in the waveguide region [Fig. 3(b), $t = 0.8t_{\text{pass}}$], and the pulse propagates in the waveguide at a high group velocity of $2\alpha\ell$. Then we gradually tune the side cavities into resonance with the pulse while detuning the waveguide out of resonance, until the field is almost completely transferred from the waveguide to the side cavities [Fig. 3(b), $t = 2.0t_{\text{pass}}$], and the group velocity becomes greatly reduced. Empirically, we found that a simple modulation [$\exp(-t^2/t_{\text{mod}}^2)$] with $t_{\text{mod}} = 10/\beta$ is sufficient. While modulation of only either the side or the waveguide cavities is sufficient, modulating both cavities with equal strength minimizes the frequency shift required. With the waveguide out of resonance, the pulse is held in the side cavities [Fig. 3(b), $t = 5.0t_{\text{pass}}$] and shows little forward motion over the time period of $3t_{\text{pass}}$ except phase change. After an arbitrarily selected delay of $5.0t_{\text{pass}}$, the pulse is released by the same process repeated in reverse, with the side cavities gradually detuned off resonance while the waveguide is tuned into resonance [Fig. 3(b), $t = 6.5t_{\text{pass}}$]. The pulse intensity as a function of time in the last waveguide cavity is plotted in Fig. 3(a) and has the same shape as both the pulse propagating through the waveguide by
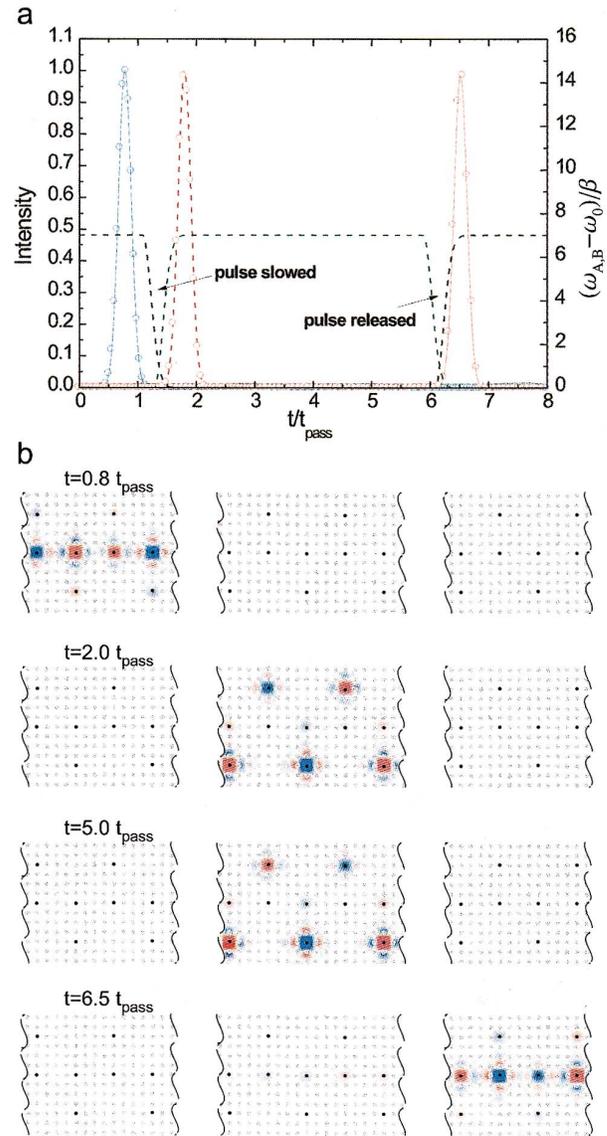
FIG. 3 (color). Propagation of an optical pulse through a coupled microcavity complex in a PC as the resonant frequencies of the cavities are varied. The PC consists of 100 cavity pairs. The pulse is generated by exciting the first cavity, and the excitation reaches its peak at $t = 0.8t_{\text{pass}}$, where t_{pass} is the traversal time of the pulse through the waveguide by itself. Fragments of the PC are shown in (b). The three fragments correspond to cavity pairs 3–6, 56–60, and 97–100. The dots indicate the positions of the dielectric rods. The black dots represent the cavities. (a) The dashed green and black lines represent the variation of ω_A and ω_B as a function of time, respectively. The blue solid line is the intensity of the incident pulse as recorded in the first waveguide cavity. The red dashed and solid lines represent the intensity in the last-waveguide cavity, in the absence and in the presence of group velocity reduction, respectively. The group velocity reduction occurs from $1.0t_{\text{pass}}$ to $1.5t_{\text{pass}}$. The pulse is then held near stationary in the system until $6.0t_{\text{pass}}$. Afterwards, the pulse is completely released at $6.5t_{\text{pass}}$. Open circles are FDTD results, and the red and blue lines are from coupled mode theory. (b) Snapshots of the electric field in the PC at the indicated times. Red and blue represent large positive and negative electric fields, respectively. The same color scale is used for all the panels.

itself and the initial pulse. Thus, our simulation demonstrates that the pulse is perfectly recovered without distortion after the intended delay of $5.0 t_{\text{pass}}$, and the FDTD simulation agrees perfectly with coupled mode theory. In the FDTD simulations, we choose an index modulation of 8% and a modulation rate of 5 GHz to make the simulation time feasible. The simulation demonstrates a group velocity of $10^{-4}c$ for a 4 ps pulse at 1.55 μm wavelength. Such a group velocity is at least 100 times smaller than the minimum group velocity achievable for such a pulse in any slow-light structure.

In practical optoelectronic devices [25], the modulation strength $(\delta n/n)$ is approximately 10^{-4} at a maximum speed exceeding 10 GHz. Since such modulation strength is far weaker compared with the FDTD simulation here, the coupled mode theory should apply even more accurately in practice. Therefore, using coupled mode theory, we simulated the structure in Fig. 1 with two side cavities. We use $\beta_1 = 10^{-5}\omega_A$, $\beta_2 = 10^{-6}\omega_A$, a maximum index shift of $\delta n/n = 10^{-4}$, a cavity loss rate of $\gamma = 4 \times 10^{-7}\omega_A$ as demonstrated for on-chip microcavities [18], and $\alpha = 10^{-5}\omega_A$ to accommodate a 1 ns pulse. The bandwidth compression occurs in two stages, first by transferring the field from A to B_1, and then from B_1 to B_2. This process reduces the group velocity to below 0.1 m/s. The same process reversed recovers the original pulse without any distortion in spite of the loss. At such low speeds, the storage times are limited only by the cavity lifetimes independent of the pulse bandwidths, which enable the use of high quality microcavities to store short (large bandwidth) pulses coherently. The losses can also be counteracted by using gain mediums [26].

The required number of cavities is determined by the length of the optical pulse in the waveguide and the propagation distance during the first field transfer stage. Using a large coupling between the side cavities B_1 and waveguide cavities A, a fast initial slow down of the pulse is achieved without violating adiabaticity. For the two-stage system presented above, the entire process of slowing down and recovering requires 120 waveguide cavities modulated below 1 GHz. Thus, chip scale implementation is foreseeable, promising on-chip quantum information processing and dramatic enhancement of nonlinear effects.

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