Ultrashort pulse propagation at the photonic band edge: Large tunable group delay with minimal distortion and loss

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We examine optical pulse propagation through a 30-period, GaAs/AlAs, one-dimensional, periodic structure at the photonic band-edge transmission resonance. We predict theoretically—and demonstrate experimentally—an approximate energy, momentum, and form invariance of the transmitted pulse, as well as large group index (up to 13.5). The group index is tunable and many orders of magnitude more sensitive to variation in material refractive index than for bulk material. We interpret this observation in terms of time-dependent electromagnetic states of the pulse-crystal system. [S1063-651X(96)50108-X]

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We report strong theoretical and experimental evidence that an ultrashort optical pulse—incident near the first transmission resonance of a compact photonic band-gap (PBG) structure—excites an unusual state. This state shows marked transient electromagnetic field localization and a close approach to invariant transmission of the pulse. Our simulations imply that this unusual combination of properties results from a coherent, resonant, momentum exchange between the ultrashort pulse and the structure. A spatial separation of the optical electric and magnetic fields mediates this exchange and results in transient energy storage in a quasi-standing-wave within the device.

Recent theoretical work by our group demonstrates the existence of a series of N transmission resonances in each pass band for a one-dimensional, N-period, layered structure. Each of these resonances exhibits peak transmittance near unity and large group index [1]. The most pronounced combination of these properties occurs at the resonances closest to the band gap—the band-edge resonances—where we carry out our experiment. The resulting combination of nearly invariant transmission and large adjustable group delay for ultrashort electromagnetic pulses in the linear regime provides a valuable and previously unavailable capability.

This current work emerges from our previous studies relating to ultrashort pulse propagation [2,3] and atomic emission rates [4,5] in one-dimensional PBG structures—a part of our overall program to develop an understanding of PBG crystals in higher dimensions [6,7]. We also note that this combination of efficient transmission and strong transient localization provides a long-sought phenomenon important to optimal optical switching [8]. Previous experiments by Chiao and co-workers have investigated the group delay of single-photon pulse propagation through one-dimensional (1D) PBG crystals at midgap frequencies [9]. But our work here is an investigation of ultrashort pulse propagation at the photonic band-edge resonance.

We show in Fig. 1 the theoretical transmittance T (dashed) and group index $n_g = c/v$, (solid) of our 30-period GaAs (107.3 nm)/AlAs (124.6 nm) sample (plotted versus midgap-normalized wavelength) at the long-wavelength edge of the photonic band gap. We define group delay by

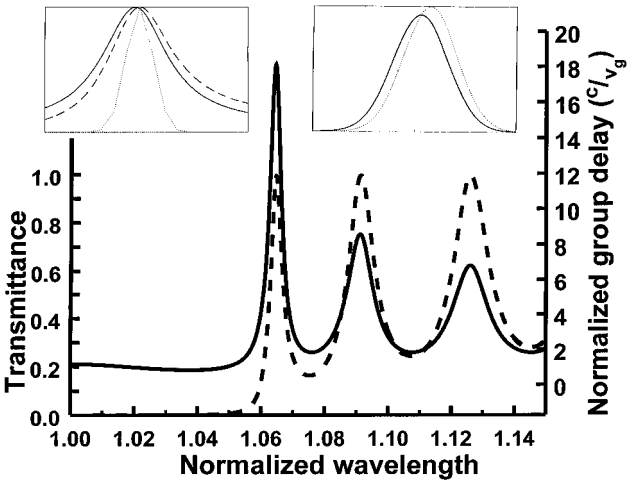

FIG. 1. Transmission curve T (dashed) and the group index $n_g = c/v_g$ (solid), versus midgap-normalized wavelength, for a free-standing, 30-period, 1D, quarter-wave, GaAs/AlAs, PBG structure. In the passband there are a series of 30 resonances where T is nearly unity and n_g is also locally maximal. (Three of these resonances appear here.) The absolute maximum in n_g is at the band-edge resonance, as shown. left inset: enlarged view of the n_g curve (solid) at the long-wavelength band-edge resonance, with a dotted line representing the bandwidth of 2 ps pulse that fits well within the transmission resonance (dashed line). Right inset: simulated comparison of the peak-to-peak group delay of a 2 ps pulse that propagates through the crystal at the band edge (solid) to a control pulse in bulk material (dotted).

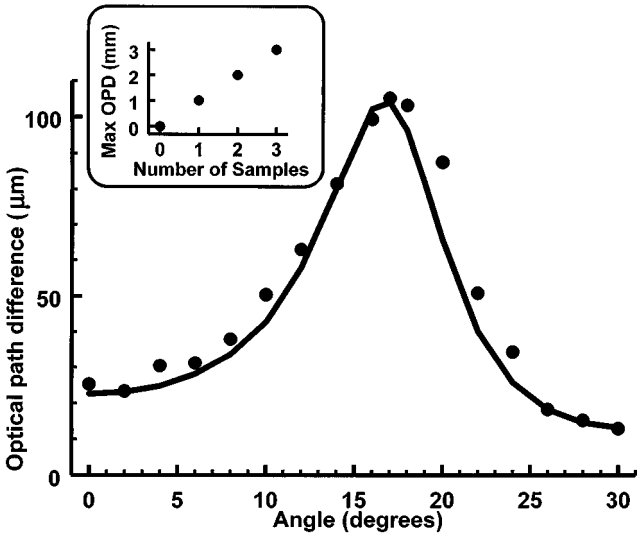

FIG. 2. Data (dots) and theory (solid) for the optical path difference versus sample angle, which is a measure of the group delay, $d=(n_g-1)L$. (Here, we subtract the delay due to the substrate.) The error in the data on the vertical axis is about ~ 4 μm. Inset: linearly accumulated delay obtained by arraying 0–3 samples in a row. (Here, we have not subtracted the additional optical path in the substrates. The delay in both PBG crystals and substrates accumulates linearly.)

$d=(n_g-1)L$, where L is the length of the sample. This particular band-edge detuning of the wavelength away from the midgap Bragg condition results in efficient transmission with minimal distortion, while also increasing the group index by an order of magnitude or more compared to free space. The leftmost inset of Fig. 1 shows the spectrum of a 2 ps optical pulse, centered at the first transmission resonance. The rightmost inset shows the simulation of a 2 ps Gaussian pulse transmitted through the photonic crystal (solid) versus the same pulse transmitted through the same length of bulk material (dotted). This pulse transmitted through the (simulated) 7 μm thick sample is delayed by nearly 110 μm, roughly corresponding to a group index of $n_g=c/v_g=17$. We obtain similar results using matrix transfer theory, Fig. 1 (see for example Refs. [1,2,5]). The preservation of pulse shape and amplitude is evident.

Our theoretical model also predicts that the group index is very sensitive to the local material index. The variation $\delta n_g/\delta n$ in the group index, with respect to either of the two indices $n=n_1$ or n_2 making up the PBG, increases exponentially with the number of periods N in the photonic crystal [1]. This increase comes at some price in bandwidth $\Delta\omega$ of the transmission resonance, which decreases exponentially with N, but not quite as rapidly as $\delta n_g/\delta n$ increases. For our 30-period structure, $\delta n_g/\delta n$ is three orders of magnitude greater than that for an equivalent amount of bulk material, and the resonance bandwidth is 2.3 nm. For a 50-period structure, $\delta n_g/\delta n$ is four orders of magnitude larger than the bulk value, and the resonance bandwidth is 0.68 nm.

We obtained experimental verification of the predictions by measuring the group delay as a function of sample orientation relative to the direction of incidence of the ultrashort optical pulse (see Fig. 2). Varying the crystal orientation tunes the transmission resonance relative to the pulse spectrum. We calculated the resulting orientation-dependent delay by the matrix transfer method [1,2,5], and by pulse propagation simulations. The calculated delay agrees well with our experiment. We have also measured experimentally the transmission T as a function of crystal orientation. We find a similarly good agreement between experiment and theory. The maximum group delay closely coincides with maximum transmission, as predicted [1]. Comparison of the theoretical and experimental transmission plots, incidentally, provides a precise measure of the crystal's periodicity. We found the period to be within 0.43% of the designed specifications. The simulations reinforce the conclusion that this atomic layer scale precision is important to obtaining the observed phenomena.

We performed the experiment by introducing the PBG crystal in one arm of our autocorrelator and then measuring the change in optical delay as a function of crystal orientation. We used a harmonically mode-locked erbium fiber laser with wavelength 1.529 μm, a repetition rate of 1.8 GHz, and nonlinear polarization-shaping to reduce the pulse duration to 2 ps [10]. We obtained each data point by averaging six autocorrelation traces. The one σ deviation in precision was approximately 1 μm of optical path delay. The available angular stage limited the angular measurement precision for the crystal to $\pm 0.25°$.

The sample included a 1.214 μm spacer of AlAs as a stop etch and a GaAs substrate 355 μm thick. We designed the structure so that the long-wavelength band edge approximated the wavelength of the test laser (1529 nm). We determined the delay due to the PBG structure by etching off the crystal's superstrate in one region of the sample, measuring the net optical delay for the substrate with the layered structure, and then the delay for the substrate alone. We plot the difference in optical delay in Fig. 2 as a function of crystal orientation. The maximum delay was 108 μm at a 17° angle of incidence. For our 8 μm thick layer (spacer plus PBG), this corresponds to a group index of $n_g=13.5$. (The spacer and substrate cause a small reduction in group index compared to the case, Fig. 1, of the free-standing PBG structure.) We note the group index at 1.529 μm in bulk GaAs is $n_g=3.55$. The maximum transmittance not including losses at the substrate interface, was about 95%. For comparison, the optical path change in bulk GaAs for the experimental angular change would be less than 1% or about 2 μm.

We found we gain additional tunable group delay, also with nearly invariant transmission of pulse form and energy, by adding several similar structures in a linear array. In this experiment, we left the PBG crystals on their substrates. The group delay accumulates linearly with the number of crystals—with no measurable distortion of pulse shape (see inset in Fig. 2). The substrates, however, prevented exploration of an arrangement of more than two crystals closer together than the substrate thickness.

We did explore sequences of more closely spaced structures using simulations. The simulations indicate that, as one places additional samples closer than half a pulse width, feedback begins to perturb the structure of the band-edge transmission resonance. This alters the group index (shown in Fig. 1), and one must then treat the array of individual crystals as a single, extended, photonic band-gap structure. We are currently exploring this latter case.

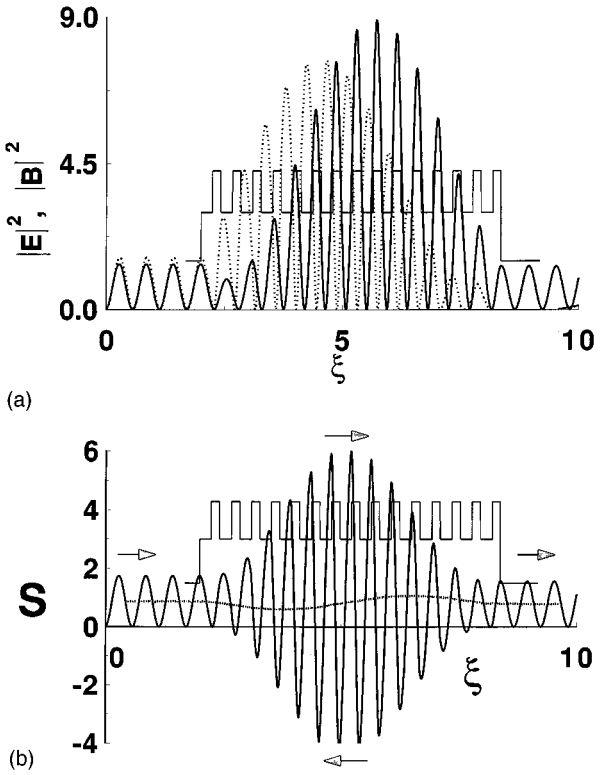

FIG. 3. (a) An illustrative plot of the instantaneous electric $|\mathbf{E}|^2$ (solid) and magnetic $|\mathbf{B}|^2$ (dashed) field profiles of a simulated, ultrashort pulse, tuned to the first band-edge resonance of a 1D PBG crystal. We also plot the index profile (not to scale). Notice that deep inside the crystal the **E** and **B** fields are almost completely out of phase. (b) A plot of the spatial distribution of electromagnetic momentum (Poynting vector) corresponding to the same case depicted in (a). Points above the axis correspond to momentum propagating to the right and points below the axis correspond to momentum propagating to the left (as indicated by arrows). We also plot the mean local momentum averaged over a unit cell (dotted line). We find that the mean local momentum is always positive, corresponding to net forward-propagating momentum. We also find momentum (and energy) scatters from the forward-propagating field into the quasi-standing-wave in the first half of the photonic crystal and then scatters back from the quasi-standing-wave into the forward-propagating fields in the second half of the crystal.

We use results of our simulations to gain insight into the physical origin of this unusual excited state. We plot in Fig. 3(a) the spatially distributed, instantaneous electric (solid) and magnetic (dashed) field intensity of the ultrashort pulse. We show the intensity at the entrance to, within, and at the exit from the photonic crystal for an instant when the pulse is approximately halfway through the structure. We plot in Fig. 3(b) the instantaneous momentum (solid). We also plot (dotted) the same momentum averaged over a unit cell of the structure, in Fig. 3(b). Both plots are for the same instant in the transmission process. The local momentum, averaged over a unit cell, is useful in visualizing the relationship between the local value of the net forward-directed momentum and the stored momentum in the quasi-standing-wave generated inside the crystal. Here, we give the Poynting vector, $\boldsymbol{S}=\boldsymbol{E}\times\boldsymbol{B}$, normalized in units of $c/4\pi$. The strong localization of the electromagnetic energy within the crystal is coincident with a marked spatial separation of the electric and magnetic fields, described in Ref. [3], and is the reason for the reduction in group velocity. This case also shows a displacement of the electric and magnetic field envelopes.

A simple way of interpreting these figures is as a combination of the forward-propagating electromagnetic field of the ultrashort pulse and a quasi-standing-wave that transiently forms within the layered structure. (We use the term quasi-standing-wave to highlight the fact that the wave retains net forward momentum, contrary to a true standing wave, whose net momentum is zero.) In this model, energy is scattered from the forward-propagating fields into the quasi-standing-wave, back into the forward-propagating fields. Inside the crystal, the wave oscillates within the central region of the PBG structure carrying—and transiently storing—substantial electromagnetic energy in a circulatory manner. The case depicted in Fig. 3 is near the peak of the pulse. As might be expected, the transfer from the forward-propagating wave to the quasi-standing-wave is larger than the inverse process when the leading edge of the pulse is entering the crystal. The reverse is true for the trailing edge of the pulse.

We note that this highly dynamic state plays a key role in producing the observed phenomena of high transmission and large group index. In particular, we find the additional anomalous momentum and energy flow (we have related this flow to interference effects [3]) is central to our understanding of the momentum exchange mechanism. This additional anomalous energy and momentum flow gives this process much of its unusual character.

These simulation techniques [2,3] also describe quantitatively the transfer of substantial net momentum from the pulses to the crystal, as well as the inverse process. The only change is a strong group delay for the ultrashort pulse. We find a roughly 20–40 % transfer and reacquisition of momentum, for parameters typical of our experimental case. In visualizing this process, it is useful to bear in mind that this momentum transfer occurs sequentially along the length of the pulse. This is because only a fraction of the pulse is in the crystal at any one instant. (We use a crystal length short compared to the pulse length in space.) The simulations also show that the strong spatial localization of the optical field in the crystal accompanies a complementary strong delocalization of the optical field in momentum space, as suggested by Fig. 3(b).

In conclusion, we find the group index for an optical pulse can exhibit a dramatic increase when we spectrally match the pulse to the first transmission resonance of a compact, 1D, PBG structure. Strong transient localization of the optical energy inside the sample provides a large and sensitively adjustable group delay. This occurs in combination with a close approach to invariant transmission of pulse form, energy, and momentum. These properties follow naturally from application of Maxwell's equations to the combined system of sample and ultrashort optical pulse. Furthermore, we demonstrate that this group-delay phenomenon accumulates linearly for a sequence of similar devices. Arrays of relatively closely packed PBG structures of this kind appear capable of providing very large adjustable group delays.

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