Ultrafast response of photonic crystal atoms with Kerr nonlinearity to ultrashort optical pulses

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We investigate the response of photonic crystal (PC) atoms with Kerr nonlinearity to the excitation of ultrashort optical pulses. Surprisingly, it is found that PC atoms with sharp resonant peaks in frequency spectrum (or with large quality factors) can respond to ultrashort pulses very rapidly when Kerr nonlinearity is introduced. More interestingly, the response time under high-power densities can be even shorter than the duration of the pump pulse. It is revealed that the nonlinearity induced broadening of dynamical frequency spectrum is responsible for the ultrafast response time, implying the possibility of ultrafast all-optical switching. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1764603]

In the last decade, photonic crystals (PCs) formed by periodic modulation of dielectric constants have been widely used as a platform to manipulate the flow of light and to realize various functional devices.[1] It has been generally recognized that PCs with imperfections or defects are much more interesting and useful than perfect PCs. As the simplest version of PC defects, a single PC defect, which is sometimes referred to as a PC atom, has been extensively studied and explored for various applications. They have not only been used independently in making filters and lasers but also been employed jointly with line defects in building channel drop filters.[2–5] It was also proposed that a single PC atom with nonlinearity can be utilized to construct a high-efficiency all-optical switch.[6,7] The switching mechanism relies on the fact that the resonant frequency of the PC defect mode will be shifted once the refractive index in the defect region is modified. In this kind of switch, low switching energy is obtained only for PC atoms with sharp resonant peaks or large quality (Q) factors. However, large Q factors imply a long lifetime for photons that sets a limit for the switching speed.[6]

The above argument for switching speed sounds quite reasonable. Even though the response of nonlinearity to optical pump is instantaneous (e.g., Kerr effect), the switching speed is ultimately determined by the photon lifetime in PC atoms. However, it has not been realized that the photon lifetime in PC atoms may be dramatically changed when nonlinearity is introduced, especially for an instantaneous one. So far, PC atoms made of semiconductors (e.g., Si/SiO_2 and $GaAs/Al_xGa_{1-x}As$) have been fabricated.[2,8] On the other hand, it is noticed that semiconductors, such as GaAs and $Al_xGa_{1-x}As$, possess very large Kerr-type nonlinear coefficient at their half-gap energies.[9] It implies that in practice we can selectively introduce an instantaneous nonlinear refractive index change (or Kerr-type nonlinearity) in the defect region where the electric-field intensity is strongly localized by utilizing a virtual two-photon absorption process. Therefore, how PC atoms with Kerr nonlinearity respond to ultrashort pump pulses became the focus of our investigation. This issue is not only important for fundamental physics but also attractive for practical applications such as the ultrafast all-optical switching mentioned above.

In this letter, we show by numerical simulation that PC atoms with Kerr nonlinearity can respond to ultrashort pulses very rapidly. It means that the introduction of nonlinearity into PC atoms will markedly modify the local photon lifetime. Also, it is revealed that the dynamical shift and broadening of the frequency spectrum are responsible for the ultrafast response time.

The PC atom studied in this letter is schematically shown in Fig. 1(a). It is formed by patterning a one-dimensional (1D) array of eight air holes in a GaAs ($n_0 = 3.37$) slab waveguide. The defect is introduced by increasing the separation between the fourth and the fifth air holes to $1.5a$, where a is the lattice constant of the 1D PC. The radius of the air holes is chosen to be $0.3a$. For simplicity, we considered a two-dimensional structure and the transverse magnetic polarization for which a wide band gap exists from $0.1768c/a$ to $0.2655c/a$, where c is the speed of light in a

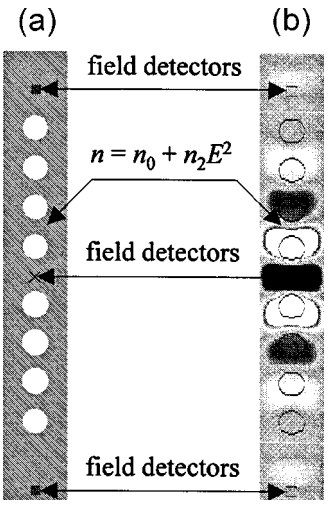

FIG. 1. (a) Schematic structure of the PC atom with Kerr nonlinearity investigated in this letter. (b) Field distribution in the PC atom.

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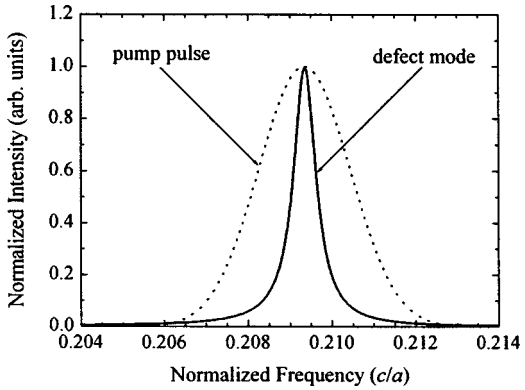

FIG. 2. Frequency spectrum of the PC atom under low excitation power density when nonlinearity is negligible. The frequency spectrum of the 237.7 fs wide pump pulse is also plotted for comparison.

vacuum. These conclusions can be naturally extended to three-dimensional structures and to transverse electric polarization. In fact, such a PC defect has been fabricated several years ago on Si/SiO_2 structures for optical filters.[2] The current fabrication technologies enable the creation of the same PC defect on GaAs/AlGaAs structures which possess very large Kerr-type nonlinearity at their half-gap energies.[8,9] Therefore, the phenomena discussed in this letter can be verified in practical experiments if both the fabrication and characterization conditions are available.

The field distribution in the PC atom is given in Fig. 1(b), showing that the field is strongly localized in the defect region. By using finite-difference time-domain (FDTD) method,[10] we calculated the frequency spectrum of the PC atom when nonlinearity is not considered or negligible. A short pulse being the fundamental mode of the slab waveguide is launched into the slab waveguide and transmitted through the PC atom. A detector is placed after the PC atom to record the transmitted intensity. Figure 2 shows the frequency spectrum of the PC atom obtained by Fourier transforming the transmitted intensity. A single defect mode located at $\sim 0.2095c/a$ could be seen. The Q factor is estimated to be ~ 323.

In order to measure the photon lifetime in the PC atom, we place a second detector at the center of the defect region, as indicated by the cross in Fig. 1(a). As the pump pulse is coupled into the defect, we see a rise of the field intensity recorded by the detector. In general, the field intensity starts to decay after the duration of the pump pulse with the exponential decay time constant corresponding to the photon lifetime in the PC atom.

Consider the situation when the defect mode is intentionally designed around the half-gap energy of GaAs. In addition, the frequency of the pump pulse is chosen to be close to the resonant frequency of the PC atom. In this case, we need to consider the nonlinearity of the PC atom when it is excited by an intense pump pulse. It means that the refractive index in the defect region is now a function of field intensity as indicated in Fig. 1 $[n(E)=n_0+n_2E^2]$. The Kerr nonlinearity, which expresses an instantaneous refractive index change proportional to the local electric-field intensity, can be easily included in the FDTD simulation of nonlinear PCs. Thus, the response of the nonlinear PC atom to ultrashort optical pulses will be manifested by the detector placed at the center of the defect.

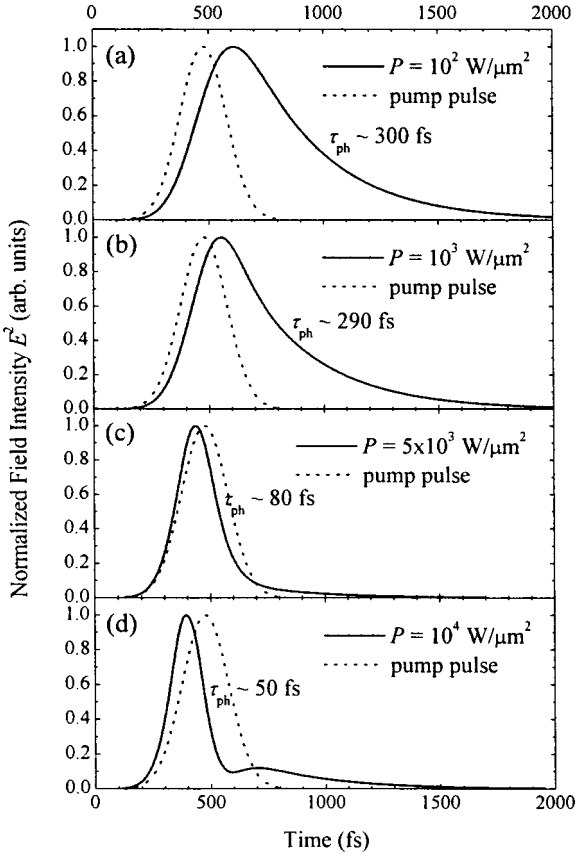

FIG. 3. Dependence of the photon lifetime in the nonlinear PC atom on the excitation power density of the pump pulse.

We chose a nonlinear coefficient $n_2 \sim 2\times 10^{-5}$ $\mu m^2/W$ (or 2×10^{-13} cm^2/W) for GaAs and neglect for simplicity the nonlinearity related to saturation. This n_2 value is similar to the reported nonlinear coefficient of GaAs.[9] The pump pulse used in the study is about 237.7 fs whose frequency spectrum is also plotted in Fig. 2. Its central frequency almost coincides with the resonant frequency of the PC atom. It can be seen that the spectral linewidth of the pump pulse is much broader than that of the PC atom, implying that only part of the pump energy can be coupled into the PC atom. We examined the response of the nonlinear PC atom to short pump pulses with different power densities. Results are presented in Fig. 3. At low power densities, we can see slow rise and decay times ($\tau_{ph} \sim 300$ fs) for the photons coupled into the PC atom. It is consistent with the large Q factor of the PC atom. With increasing power density, however, a dramatic decrease in both the rise and decay times is observed. The decay times at $P=5\times 10^3$ and 1×10^4 $W/\mu m^2$ are estimated to be approximately 80 fs and 50 fs, respectively. Surprisingly, the decay time at high-power densities is even shorter than the duration of the pump pulse, as shown in Fig. 3. This is an exciting behavior of nonlinear PC atoms which breaks the limit set by the lifetime of photons in linear PC atoms and implies the possibility of realizing ultrafast all-optical switch. It is also noted that a second rise and decay process appears for high-power densities. It is confirmed (not shown here) that the field intensity in the PC atom under very high-power densities exhibits an oscillation with attenuated intensity and elongated time constant.

It is thought that the remarkable phenomena observed in Fig. 3 originate from the dynamical shift of the frequency

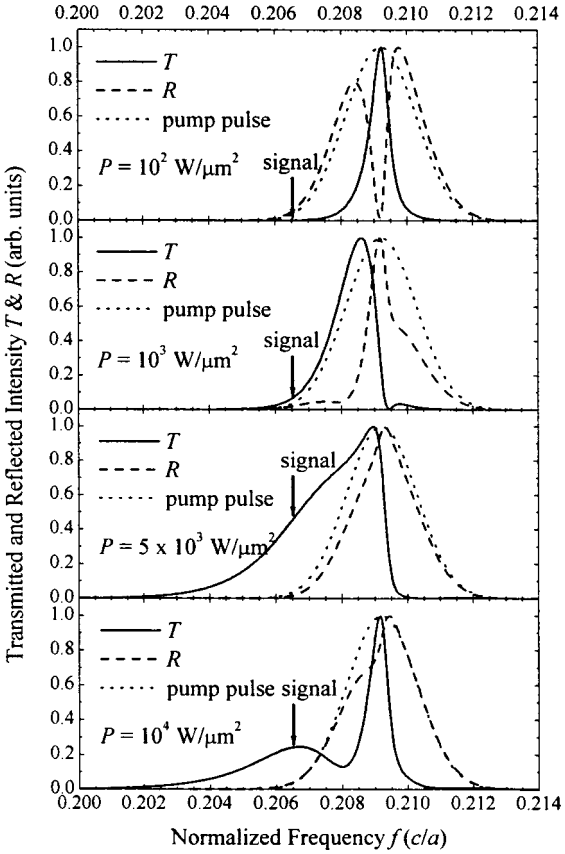

FIG. 4. Pump power dependence of the transmitted and reflected spectra. In order to compare the spectral shape, both the transmitted and reflected intersities are normalized to 1.0. The spectrum of the pump pulse is also plotted for reference. The arrows indicate the location for the signal pulse in an all-optical switch.

spectrum of the PC atom, leading to the significant broadening of the spectral linewidth. The significant broadening of the frequency spectrum is responsible for the dramatic reduction of photon lifetime. In order to gain a deeper insight into this behavior, we have calculated the Fourier transformations of the transmitted and reflected intensities which give the transmission and reflection spectra of the nonlinear PC atom, as shown in Fig. 4. Clearly, we can find the broadening of both the transmission and the reflection spectra. Particularly, we observe two resonant peaks with different linewidths at $P=1\times10^4$ W/μm^2 which correspond to the two rise and decay processes observed in Fig. 3.

In this letter, we discuss nonlinear PC atoms in which the response of nonlinearity to optical pump is instantaneous (e.g., Kerr effect). For applications of all-optical switch, the switching mechanism must be slightly modified as compared to that proposed by Villeneuve *et al.*[6] In our case, it is necessary to set the wavelength of the signal pulse far from the resonant peak of the PC atom, as indicated by arrows in Fig. 4. In the absence of an optical pump, the signal pulse is totally blocked and it corresponds to the OFF state of the switch. In the presence of a strong optical pump (a control pulse), the significant broadening of the frequency spectrum of the nonlinear PC atom leads to the fast transmission of the signal pulse, suggesting a promising ultrafast all-optical switching mechanism. It should be noted that the spectral linewidth of the pump pulse used in this study is much broader than that of the PC atom. Thus, a high pump power density is needed in order to observe the ultrafast response of the PC atom as only a small amount of pump energy couples into the PC atom. This power density will be significantly reduced by using a relatively longer pump pulse (e.g., 500 fs).

Before drawing conclusions, it is worth mentioning that recently the temporal coupled-mode (CM) theory has been employed to account for the dynamics of a bistable all-optical switching and excellent agreement between the CM theory and FDTD simulations has been achieved.[11] With some modifications (e.g., including the dependence of the photon lifetime in the cavity on the excitation power density), the temporal CM theory may become an useful analytic tool for describing the dynamics of nonlinear PC atoms.

In summary, we have investigated the response of nonlinear PC atoms to ultrashort optical pulses. It is found that very rapid response time can be achieved at high-power densities when nonlinearity becomes effective. It is shown that the response time can be even shorter than the duration of the pump pulse and that there is a dynamic broadening of the frequency spectrum. Our study indicates that nonlinearity in PC atoms helps overcome the limitation on response speed set by the long photon lifetime. Thus, with the present fabrication techniques, nonlinear PC atoms could be employed to realize a highly efficient ultrafast all-optical switch.

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