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REVIEW ARTICLE

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Ultrafast photonic crystal optical switching

Abstract Photonic crystal, a novel and artificial photonic material with periodic dielectric distribution, possesses photonic bandgap and can control the propagation states of photons. Photonic crystal has been considered to be a promising candidate for the future integrated photonic devices. The properties and the fabrication method of photonic crystal are expounded. The progresses of the study of ultrafast photonic crystal optical switching are discussed in detail.

Keywords photonic crystal, optical switching, third-order optical nonlinearity

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Photonic crystals are novel and artificial photonic materials with periodic dielectric structures, designed to modulate the propagation states of photons and tailor the properties of electromagnetic modes in much the same way that the semiconductor materials control the propagation properties of electrons [1]. Since Yablonovith [2] and John [3] presented the concept of photonic crystal in 1987, great efforts have been made to study the properties of photonic crystals and their applications in the fields of integrated photonic circuits and ultrahigh information processing. Optical switching is an essential component of integrated photonic circuits. The properties of photonic crystal and the progresses of the study of ultrafast photonic crystal optical switching are discussed.

1 Properties of photonic crystal

For a semiconductor crystal, the periodic distribution of atoms in space constructs the crystal lattice, which imposes a periodic potential on electrons propagating through it. Owing to the Bragg diffraction of atoms, electrons with certain energy are forbidden to propagate in certain directions, which leads to the formation of bandgap in the energy band structures of semiconductor materials. Similarly, the spatially periodic distribution of dielectric medium provides the periodic potential for photons propagating in a photonic crystal. If the dielectric constant contrast of the media constructing the photonic crystal is large enough, the photonic bandgap will be generated by the Bragg scattering of photons in the interfaces of different medium. Photonic bandgap prevents light from propagating in certain directions with certain energies [4]. When the dielectric contrast is larger than the threshold value of 2.8, light with any polarization incident at any angle in some frequency range will be reflected by the photonic crystal [5] . This leads to the formation of the complete photonic bandgap.

According to the periodicity of dielectric materials along different axes, photonic crystal can be divided into one-, two- and three-dimensional photonic crystal. The dielectric materials of one-dimensional photonic crystal are only periodic in one direction. One-dimensional photonic crystal, also called quarter-wave reflector, has a multilayer stack structure with alternating high refractive index material and low refractive index material, as shown in Fig. 1. The thickness is $\lambda/4n_1$ for high refractive index material and $\lambda/4n_2$ for low refractive index, where λ is the free-space wavelength, n_1 is the refractive index of high dielectric material, n_2 is the refractive index of low dielectric material [6]. The photonic bandgap emerges only in the direction perpendicular to the dielectric layer. The light with wavelength in a range centered at λ will be reflected completely by the one-dimensional photonic crystal when it is incident in the direction perpendicular to the dielectric layer. The dielectric periodicity of two-dimensional photonic crystal is along the x and y axis. The dielectric materials are homogeneous along the z axis. The propagation properties of light in a two-dimensional photonic crystal is modulated by the photonic bandgap in the x-y plane and controlled by the total-internal reflection in the direction of z axis. For a

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three-dimensional photonic crystal, the dielectric periodicity is along three axes. According to the Bragg diffraction condition, the central wavelength λ of the photonic bandgap of a three-dimensional photonic crystal can be obtained[7]:

$$m\lambda = 2d_{hkl}(\overline{n}^2 - \sin^2\theta)^{\frac{1}{2}} \quad (1)$$

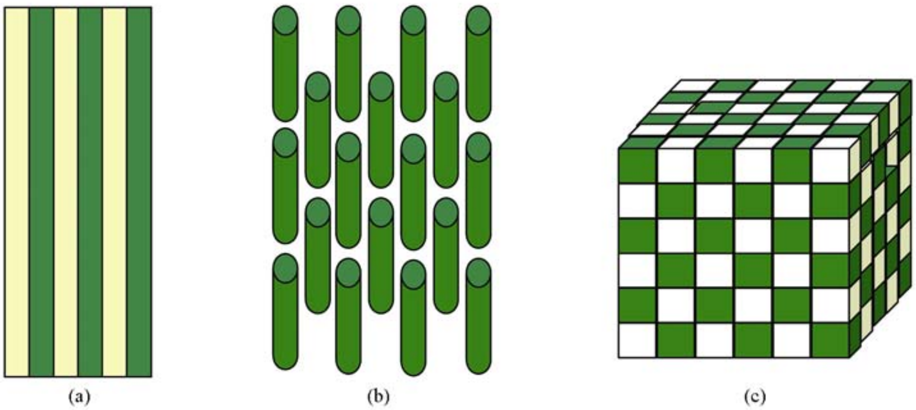

Fig. 1 Schematic structure of photonic crystal. (**a**) For one-dimensional photonic crystal. (**b**) For two-dimensional photonic crystal. (**c**) For three-dimensional photonic crystal.

where m is the diffraction order, d_{hkl} is the spacing between (hkl) planes, $\overline{n}$ is the effective refractive index of the photonic crystal, θ is the angle between the incident light and the direction normal to the diffraction planes. θ is equal to zero for normal incidence.

For a perfect photonic crystal, the photonic density of state is zero in the photonic bandgap. Light whose frequency is inside the photonic bandgap decays exponentially when it enters the photonic crystal [4]. When a lattice defect is introduced into the photonic crystal, the spatial periodicity of the dielectric distribution is destroyed. According to the photon localization theory, the electromagnetic field with a certain resonant frequency will be strongly confined around the defect site, which leads to the formation of a localized defect mode with high transmittance in the photonic bandgap [8]. Moreover, like the splitting of valence electron states into bonding and antibonding states due to the coupling of two identical atom systems in semiconductor materials, the coupling of two identical defect modes makes their resonant eigenfrequency split into two modes [9,10]. Defect modes provide excellent optical channels, which has important applications in the fields of optical filters and wavelength division multiplexing (WDM) systems. When a number of identical defect units are introduced in the photonic crystal, a transmittance band in the photonic bandgap can be formed [11].

2 Fabrication methods of photonic crystal

The photonic crystal whose photonic bandgap is located in the visible and infrared range has important applications in the optoelectronic industry. Accordingly, the periodicity of the dielectric distribution of the photonic crystal is in the nanometer and micrometer range. One-dimensional photonic crystal can be fabricated by modern film fabrication technology. Microfabrication etching technology can be adopted to fabricate two-dimensional photonic crystal in metal, semiconductor or organic materials [12]. Self-assembly method [7], direct laser writing [13] and laser holographic lithography [14] are primary approaches to fabricate three-dimensional photonic crystal.

The multiphoton polymerization is used in the direct laser writing method [15,16]. More often than not, the negative photoresist SU-8 is used as the template of three-dimensional photonic crystal. A focused femtosecond laser, whose photon energy is below the single-photon polymerization threshold of the photoresist, is used to excite the negative photoresist. The laser intensity in the small volume of the focus exceeds the threshold of multiphoton polymerization. Upon the irradiation of laser pulse, the photoinitiator in the photoresist creates acid, which can catalyze the cross linking reaction of the monomers to the polymer. A solvent in the following development process removes the insufficiently cross-linked photoresist in the underexposed regions. Deubel *et al.*[15] fabricated a three-dimensional photonic crystal with the slant pore structure by the direct laser writing method, as shown in Fig. 2. Campbell *et al.* developed the laser holographic lithography method in 2000 [14].The periodic microstructure of three-dimensional photonic crystal is generated by the interference of several noncoplanar laser beams in a photoresist film. The unexposed areas are removed and the exposed areas construct the three-dimensional photonic crystal.

Colloidal crystal and opal, belonging to three-dimensional photonic crystal, can be fabricated by the self-assembly method. The colloidal crystals are formed mainly by the electrostatic interaction of charged colloidal particles in the deionized state [17]. Park [18] injected the suspension of colloidal particles into a cell formed by two glass substrates and a square frame of photoresist. One side of the frame was patterned with channels that could retain the colloidal particles and make the solvent flow out of the cell. Opal with face-centred cubic (FCC) structure could be obtained in about one week. The fabrication process could be accelerated by use of external gas pressure and sonication. The formation process of the three-dimensional photonic crystal can not be controlled easily in the self-assembly method. As a result, there are numerous lattice defects in the photonic crystal. Denkov *et al.* proposed the idea of the vertical deposition method in 1992 [19]. When a hydrophilic substrate is vertically dipped into the colloidal suspension containing microspheres and water, a meniscus region is formed between the substrate and the horizontal surface of the suspension due to the wetting action of water. The microspheres at the meniscus region are forced to construct a ordered FCC structure on the surface of the substrate by the lateral capillary forces and the hydrodynamic pressure of the water influx as the meniscus is slowly swept downwards across the substrate with the evaporation of water [20]. The growth process of the photonic crystal can be controlled in part through adjusting the external parameters, such as the surrounding temperature and humidity. High quality three-dimensional photonic crystal can be obtained by this method.

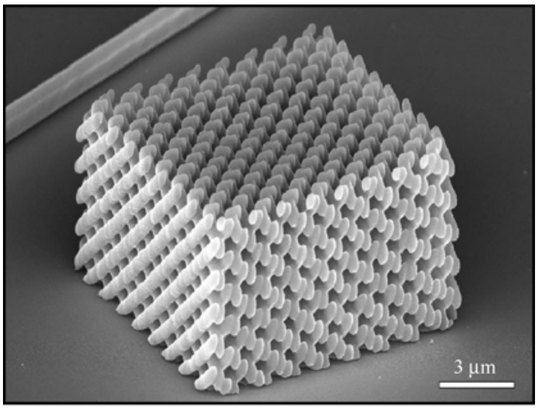

Fig. 2 Scanning electron microscopoy image of a three-dimensional photonic crystal fabricated by the direct laser writing method.

3 Theoretical study of photonic crystal optical switching

In 1994, Scalora et al. presented that the optical switching could be achieved by use of photonic bandgap shift induced by a pump laser [21]. The wavelength of the probe light is set near the photonic band edge. At first, the probe light is reflected completely by the photonic crystal and the optical switching is in the “off” state. Under the excitation of a pump laser, the refractive index of the third-order nonlinear medium in the photonic crystal is changed due to the nonlinear Kerr effect. This leads to the variation of the effective refractive index of the photonic crystal and the shift of the photonic bandgap. The wavelength of the probe laser is in the pass band and the probe laser can propagate through the photonic crystal now. The optical switching is in the “on” state. This mechanism is widely used by researchers in their experiments to demonstrate the photonic crystal optical switching.

Tran proposed the defect mode shift mechanism in 1997 [22]. According to the photon localization theory, defect mode will appear in the photonic bandgap when a lattice defect is introduced in the photonic crystal [8]. The wavelength of the probe laser is located in the central position of the defect mode. The probe laser can propagate through the photonic crystal and the optical switching is turned on. The photonic bandgap shifts under the excitation of a pump laser. This leads to the variation of the position of the defect mode in the photonic bandgap. The wavelength of the probe laser is far away from the central wavelength of the defect mode and the probe laser is reflected completely by the photonic crystal. The optical switching is then turned off.

Chen proposed the concept of optical bistabile switching in a nonlinear photonic crystal [23] . A lattice defect made of third-order nonlinear medium is introduced in a photonic crystal and the defect mode appears in the photonic bandgap. The wavelength of the probe laser is set near the central wavelength of the defect mode. The transmittance of the probe laser increases with the increment of the intensity of probe laser. The photon localization effect and the third-order nonlinearity can offer nonlinear feedback for the probe light. As a result, the transmittance spectrum of the probe light takes on the properties of optical bistability. When the intensity of probe laser exceeds the threshold value, the transmittance of the probe laser becomes very large and the switching is in the “on” state. When the intensity of probe laser is less than a threshold value, the transmittance of the probe laser becomes very small quickly. Then the switching is turned off.

Villeneuve *et al.* pointed out that the intensity-controlled switching could be achieved in a two-dimensional nonlinear photonic crystal waveguide coupler [24]. When the intensity of probe light is very low, the energy of the probe light in waveguide “1” is coupled into waveguide “2” in the waveguide coupling region. The probe light leaves the photonic crystal from waveguide “2” and no signal outputs from waveguide “1”. So, the optical switching is in the “on” state. With the increment of the probe light intensity, the third-order nonlinear effect becomes stronger and stronger. This results in the variation of the effective refractive index of the photonic crystal. The coupling condition can not be met satisfactorily in the waveguide coupling region. When the intensity of the probe light exceeds the threshold value, almost all the probe light propagates in waveguide “1”. The optical switching is in the “off” state.

Ultrafast optical switching can also be realized based on the changes of photonic density of states in a three-dimensional semiconductor photonic crystal [25] . Under the excitation of a short laser pulse, a large number of free carriers are generated in the semiconductor material through two-photon absorption process. This results in the variation of the effective refractive index of the photonic crystal. Accordingly, the position and width of the photonic bandgap is changed. At certain frequencies, the photonic density of states in the photonic bandgap can be switched from zero to a high value on several femtoseconds time scale. Therefore, the ultrafast optical switching can be realized.

Wang *et al.* proposed the concept of photon flux switching in a two-dimensional photonic crystal composed of dielectric nanorods [26] . When a lattice defect is introduced in the photonic crystal, photon states with certain resonant frequency will be confined in the defect site. The wavelength of the probe light is set around the central wavelength of the defect mode. When the refractive index of the lattice defect is higher than the threshold, the probe light propagates through the photonic crystal along the defect channel. The optical switching is turned on. If the refractive index of the lattice defect is lower than the threshold, the probe light propagates out of plane and transmits into free space. The optical switching is switched off. The changes of the refractive index of the lattice defect can be controlled by different methods, such as chemical, electrical and optical method.

Recently, Soljacic *et al.* presented a mechanism to demonstrate ultralow-power all-optical switching based on a hybrid system of a photonic crystal microcavity infiltrated with nonlinear ultraslow light medium [27] . Nonlinear ultraslow light medium has very large nonlinear refractive index, which decreases the required pump power threshold. Even the energy of several photons can make the optical switching operate.

4 Progress of experimental study

The photonic bandgap and defect mode shift mechanisms are widely used to demonstrate photonic crystal optical switching. Various phenomena, such nonlinear Kerr effect, electro-optic and thermo-optic effect, can be used to modulate the effective refractive index of photonic crystals. Accordingly, the shift of photonic bandgap or defect mode is controlled dynamically and the photonic crystal optical switching can be realized. As an optical switching, two key characteristics should be concerned: the switch efficiency, i.e., high intensity contrast between two states of “on” and “off”, and fast time response.

4.1 Thermally controlled photonic crystal switching

Camargo *et al.* realized a thermo-optically controlled symmetric Mach-Zehnder interferometer switching based on an AlGaAs/GaAs photonic crystal waveguide structure operating at 1540 nm [28] . A voltage-controlled heater was used to change the temperature of the semiconductor photonic crystal waveguide. The thermally induced variation of the refractive index of AlGaAs/GaAs epitaxial structure changed the phase contrast of the lights propagating in the two arms of the Mach-Zehnder interferometer. This resulted in the changes of the transmittance of the probe light. No signal outputed from the Mach-Zehnder interferometer when π-phase contrast was achieved. The transmittance contrast of the probe light was about 90 %. The response time was in the time scales ranging from millisecond to second [29].

Reese *et al.* fabricated a three-dimensional colloidal photonic crystal made of poly(*N*-isopropylacrylamide) (PNIPAM) nanogel colloidal particles by use of self-assembly method [30] . The colloidal photonic crystal was polymerized into a loose-knit hydrogel which permits the individual embedded nanogel PNIPAM particles to undergo the thermally induced volume phase transition. The polymer hydrogel was highly swollen in water at 10 °C. The volume phase transition of PNIPAM particles occurs when the environmental temperature is higher than the lower critical solution temperature (LCST) of 32 °C. Increasing the temperature above 32 °C caused the polymer hydrogel to collapse and squeeze out water, which made the nanogel particles shrink in volume. Accordingly, the lattice constant was changed. This leaded to the variation of the position of the Bragg diffraction peak. The wavelength of probe light was set at the central wavelength of the Bragg diffraction peak. The transmittance contrast of 61 % for the probe light was obtained and the response time of the switching is about 100 ns, as shown in Fig. 3.

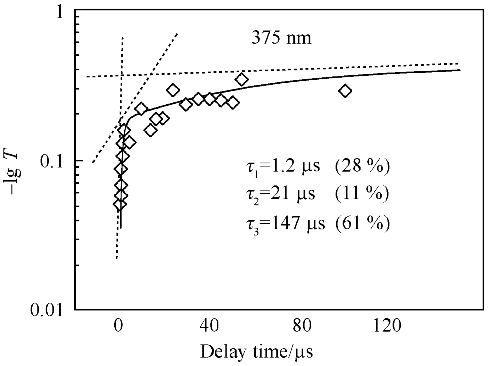

Fig. 3 Thermally controlled photonic crystal optical switching.

4.2 Photonic crystal electro-optic switch

Ozaki *et al.* reported a high-speed electro-optic switching based on the tunable defect mode in a one-dimensional photonic crystal containing a nematic liquid crystal defect layer [31] . The defect mode had a narrow spectral linewidth. Under the excitation of an electric field, the orientation of the liquid crystal molecules in the defect layer was changed. This led to the variation of the optical length of the defect layer. The position of the defect mode in the photonic bandgap was changed. The wavelength of the probe light was set at the central wavelength of the defect mode. The transmittance of the probe light was modulated by the electric field. The response time of the photonic crystal was in the order of several milliseconds and the switch efficiency was quite high.

4.3 Photonic crystal all-optical switching

For a photonic crystal all-optical switching, the switch efficiency and the response time are mainly determined by the magnitude of the third-order nonlinear coefficient and the nonlinear time response of the third-order nonlinear medium in the photonic crystal, respectively.

4.3.1 Study of high switch efficiency

Scherbakov *et al.* fabricated a high quality SiO_2 opal infiltrated with vanadium dioxide (VO_2) [32] . VO_2 undergoes a structural semiconductor-metal phase transition at T_c=70 °C, accompanied by strong changes of dielectric constant. A beam (pulse width 10 ns and wavelength 532 nm) form a YAG:Nd laser (repetition rate 1 kHz) was used to heat the opal. The energy of the laser photons exceeded the bandgap of VO_2, which led to strong linear absorption. A large number of photo-excited carriers were generated and the dielectric constant of VO_2 was changed. The reflectivity contrast of the probe light was 40 % for the opal optical switching.

Mazurenko *et al.* filled a SiO_2 opal with a mixture of nanocrystalline and amorphous silicon [33,34]. The beam (Pulse width 30 fs and repetition rate 75MHz) with wavelength of 800 nm from a Ti-sapphire laser was used as pump laser. Under the excitation of the pump laser, free carriers were generated in silicon and the effective refractive index of the photonic crystal was changed. The measured reflectivity contrast was 46% for the probe light, as plotted in Fig. 4.

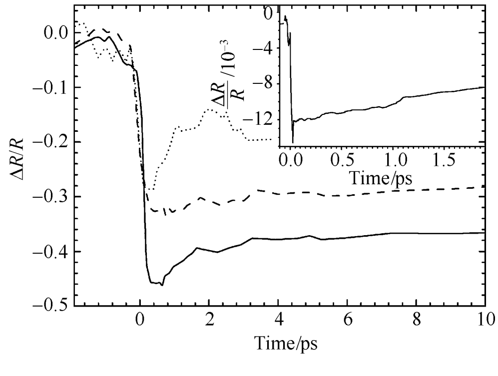

Fig. 4 Three-dimensional photonic crystal all-optical switching.

Leonard *et al.* achieved a 60 % reflectivity contrast for the probe light in a two-dimensional silicon photonic crystal optical switching, as shown in Fig. 5 [35] . Changes in the refractive index of silicon were optically induced by injecting free carriers with 800 nm femtosecond laser pulses. A large shift of the photonic band edge, about 30 nm, was obtained in their experiment. This caused the high reflectivity contrast. Zhang's group obtained 63 % transmittance contrast by use of polystyrene nonlinear photonic crystals [36,37]. The optical nonlinearity of polystyrene originates from the delocalization of conjugated π-electrons along the polymer chains, which leads to large third-order nonlinear optical susceptibility and a femtosecond response time. Under the excitation of pump laser, the refractive index of polystyrene changed, which led to the shift of the photonic bandgap and an all-optical switching was achieved.

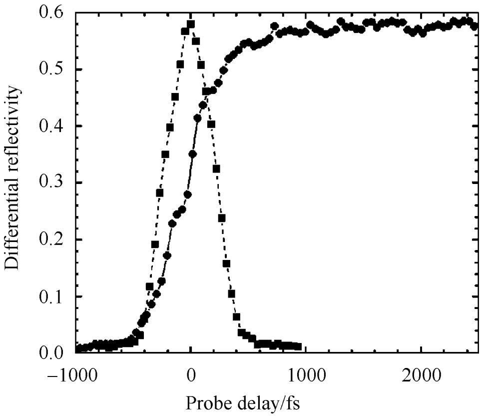

Fig. 5 Two-dimensional silicon photonic crystal all-optical switching.

Recently, Hu's group [38] achieved a very high transmittance contrast of over 70 % by using defect mode shift in a two-dimensional polystyrene photonic crystal, as depicted in Fig. 6. Focused ion beam (FIB) etching method was adopted to fabricate two-dimensional polystyrene photonic crystal with thickness of 300 nm. A line defect was introduced in the center of the photonic crystal and a high quality defect mode was obtained. The line width of the defect was 2.4 nm. The maximum shift of the defect mode was 5 nm under the excitation of pump laser and all-optical switching with high switch efficiency was realized.

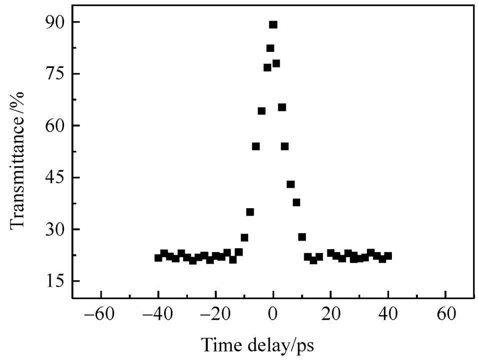

Fig. 6 Two-dimensional organic photonic crystal defect mode all-optical switching.

4.3.2 Study of fast response time

Tanabe *et al.* realized an all-optical switching in a two-dimensional silicon photonic crystal containing a nanocavity defect [39] . Under the excitation of a pump laser, free carriers were generated in silicon due to strong two-photon absorption. This resulted in the variation of the refractive index of silicon. The position of the defect mode in the photonic bandgap shifted. The time response of the optical switching was about 50 ps. Bristow *et al.* fabricated a two-dimensional AlGaAs photonic crystal by electron beam lithography and chemically assisted ion beam etching [40] . The reflectivity of the probe light was modulated by the refractive index changes of AlGaAs induced by pump laser. The response time of the optical switching was 8 ps.

Hache and Bourgeois realized an all-optical switching in a one-dimensional photonic crystal composed of alternating SiO_2 and amorphous Si layer [41] . The free carriers in silicon excited by the pump laser changed the refractive index of silicon. The transmittance of the probe light was modulated based on the nonlinear Kerr effect. The response time of the optical switching was 400 fs, as plotted in Fig. 7. Shimizu and Ishihara fabricated a photonic crystal slab, in which inorganic-organic layered perovskite semiconductor $(C_6H_5C_2H_4NH_3)_2PbI_4$ was embedded for large optical nonlinearity [42] . Under the excitation of a pump laser , the photonic bandgap shifted due to the excitonic optical Stark effect. The response time of the optical switching was 200 fs, as shown in Fig. 8.

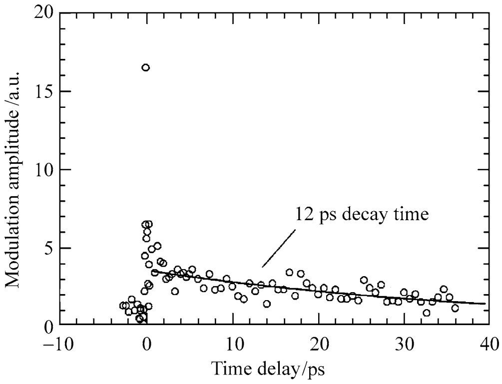

Fig. 7 One-dimensional silicon photonic crystal all-optical switching.

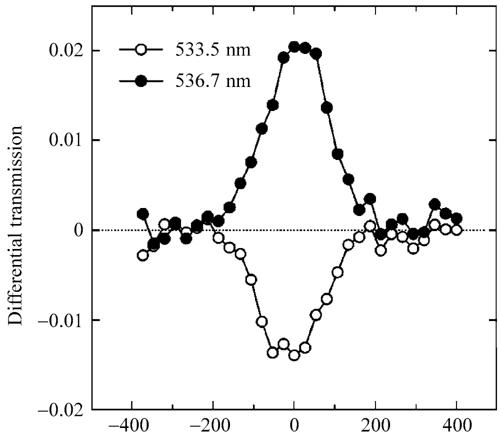

Fig. 8 Photonic crystal slab all-optical switching.

Mazurenko *et al.* achieved a 30 fs ultrafast response time for a three-dimensional Si-based photonic crystal optical switching [43,44] . They infiltrated a SiO_2 opal with mixed amorphous-nanocrystalline silicon. With the excitation of pump laser, free carriers generated in silicon changed the refractive index of silicon, which resulted in the variation of the central wavelength of the photonic bandgap. An ultrafast all-optical switching was realized, as plotted in Fig. 9.

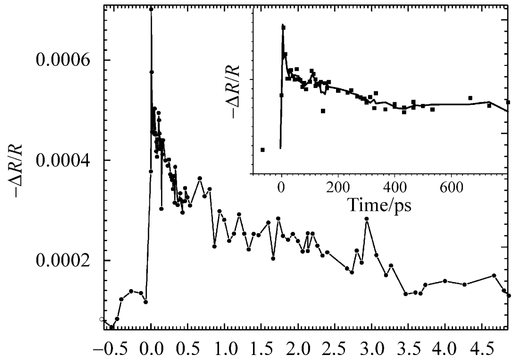

Fig. 9 Si-based opal all-optical switching.

In conclusion, we discussed the properties of photonic crystal and the progress of the study of the photonic crystal optical switching. It is still a great challenge for people to realize an ultrafast photonic crystal all-optical switching with high switch efficiency and femtosecond time response.

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