Optical tuning of three-dimensional photonic crystals fabricated by femtosecond direct writing

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In this letter, we report on an optically tunable three-dimensional photonic crystal that exhibits main gaps in the 3–4 μm range. The photonic crystal is manufactured via a femtosecond direct writing technique. Optical tuning is achieved by a luminary polling technique with a low-power polarized laser beam. The refractive index variation resulting from liquid-crystal rotation causes a shift in the photonic band gap of up to 65 nm with an extinction of transmission of up to 70% in the stacking direction. Unlike other liquid-crystal tuning techniques where a pregenerated structure is infiltrated, this optical tuning method is a one-step process that allows arbitrary structures to be written into a solid liquid-crystal-polymer composite and leads to a high dielectric contrast. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2037862]

Photonic crystals are periodic structures that manipulate and control light using multiple Bragg diffraction. The ability of photonic crystals to control light in three dimensions without loss is a key factor that makes them analogous to semiconductors with electrons.[1] The possibility of extending current optoelectronic systems to all-optical systems is an exciting prospect that has come closer to reality by fabricating three-dimensional (3D) photonic crystals.[2–10] While the fabrication methods based on Si lithography,[2,3] semiconductor wafer fusion,[4,5] and self-assembling[6] have resulted in 3D photonic crystals of complete band gaps, two-photon polymerization[7,8] and ultrafast laser driven microexplosion[9,10] provide two methods for directly writing a 3D photonic crystal of an arbitrary lattice structure. In particular, the microexplosion method[9] is a one-step process without any postprocessing resulting in microchannels that can be stacked in a 3D structure. The void dots or channels created by this method exhibit a high degree of perfection that facilitates the generation of higher-order stop gaps[10] from the 3D photonic crystal.

Another important aspect on developing 3D photonic crystals is the realization of band-gap tunability. There have been three reported methods for achieving the tuning ability of a photonic crystal, external compression of the structure,[11] temperature tuning,[12] and electrical tuning.[13–15] In particular, electrical tuning that relies on altering the refractive index of liquid crystals upon the application of an electrical field provides the advantage of integrating photonic-crystal-based devices with current electro-optic devices. Most of the developments in this area have involved the infiltration of liquid crystals into a pregenerated structure such as the inverse opal.[13] However, this method actually decreases the refractive index contrast and may be ineffective when a complicated 3D lattice structure is adopted.

To overcome this drawback, we have demonstrated electrical tuning of a liquid-crystal-based 3D photonic crystal without reducing the dielectric contrast.[15] Instead of infiltrating liquid crystals into a pregenerated void structure, we doped the liquid crystal into a host polymer to form a material known as polymer dispersed liquid crystals (PDLCs). In PDLCs, the liquid-crystal droplets are dispersed throughout the solid polymer block.[16,17] The re-alignment of liquid crystals in an external electrical field provides a mechanism for altering the refractive index of the bulk polymer composite and, therefore, for electrical tuning of 3D photonic crystals.[15]

It should be pointed out that the re-alignment of the liquid-crystal directors in PDLCs is also dependent on the polarization state of an external optical field,[17,18] which therefore provides a mechanism for optical tuning of photonic crystals with an optical modulation time of less than 50 ms. In this letter, we demonstrate an all-optical device in which the position of the photonic band gap shifts spectrally with the application of a polarized tuning beam incident on a 3D photonic crystal. In this case, the polymer used was a polyurethane oligomer having C═C unsaturation which is crosslinked by a thiol-ester oligomer (NOA63 optical adhesive, Norland Inc.; refractive index $n_{\mathrm{NOA}}=1.56$). The liquid crystal was E49 (Merck) which contains 4-pentyl 4-cyano biphenyl. It has an extraordinary refractive index (n_{LC}^{e}) of 1.74 and an ordinary refractive index (n_{LC}^{o}) of 1.53. The sample was prepared by the same method as before.[14]

The one-step multiphoton induced void channel microfabrication technique[9,10] allows the generation of arbitrary 3D hollow-spaced structures. Using this method, we focused a femtosecond pulsed laser beam into the PDLC sample to produce microvoid channels which were layered to create 3D woodpile photonic crystals [Fig. 1(a)]. The fabrication setup was similar to that which we used before.[15] To analyze the structures created, the first four layers were imaged using an Olympus IX70 microscope that had an Olympus 60× numerical aperture 1.4 infrared (IR) enhanced objective and

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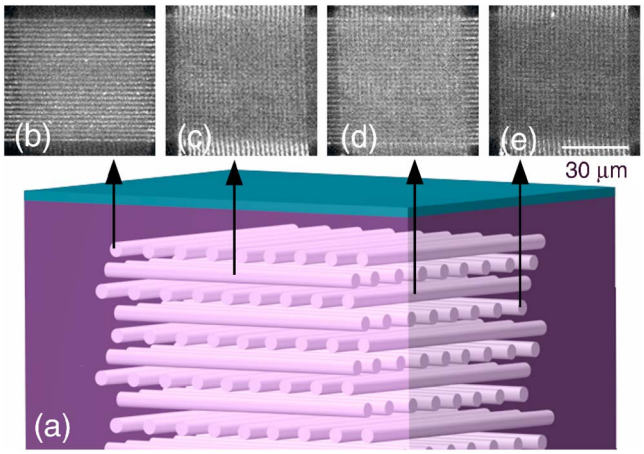

FIG. 1. Schematic diagram of a void channel woodpile photonic crystal structure (a). (b)–(e) Two-photon fluorescence images of the first four layers of the photonic crystal. The concentration of liquid crystals is 6%.

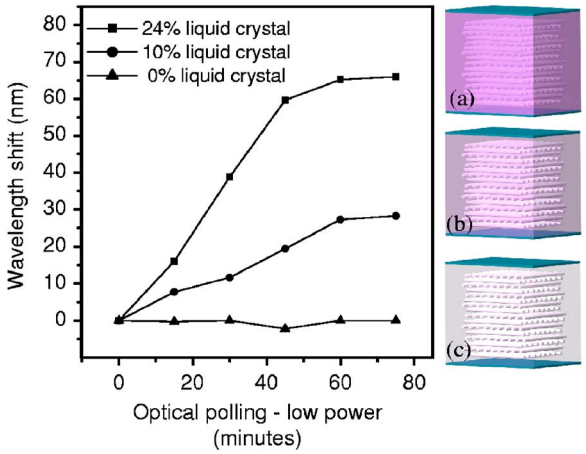

FIG. 3. Variations in the stop gap position with the application of a polarized optical field for 0%, 10%, and 24% liquid-crystal concentrations. The reference cell (0%) shows no stop gap movement as a result of the optical polling. The shading effect in (a)–(c) represents an increase in the refractive index of the bulk material with the application of optical polling to the cell.

coupled with an ultrafast pulsed laser beam operating at wavelength 800 nm. Figures 1(b)–1(e) show the four layers with (b) being the top layer and (e) being the fourth layer. The photonic crystals used in these experiments consisted of 20 layers with in-plane spacings δx and δy of 1.57 μm and a layer spacing (δz) of 1.25 μm. Such a structure provides an extinction of transmission of approximately 70% when illuminated in the stacking direction.[15] The physical reason for fluorescence of the PDLC under two-photon excitation is the re-alignment of liquid-crystal directors along the polarization direction of the illumination laser beam.[17]

The principle of optical tuning is explained in Fig. 2. The prepolled state (no optical field) sees a random liquid-crystal director alignment with its long molecular axis freely positioned at any angle resulting in a refractive index of $n_{\mathrm{LC}}^{\mathrm{prepolled}}=(n_{\mathrm{LC}}^{e}+2n_{\mathrm{LC}}^{o})/3=1.60$ [Fig. 2(a)].[19] As E49 has a positive dielectric anisotropy, the directors align parallel to an applied electric-field vector. If a linearly polarized optical beam is incident along the stacking direction of the fabricated photonic crystal, the directors rotate to align perpendicular to the stacking direction of the photonic crystal. If the laser beam is scanned along its polarization direction, this aligning process is enhanced, producing $n_{\mathrm{LC}}^{\text{optical-polled}}=n_{\mathrm{LC}}^{e}$ =1.74, as shown in Fig. 2(b). This optical polling/tuning process leads to a shift of the stop gap in the longer-wavelength direction.

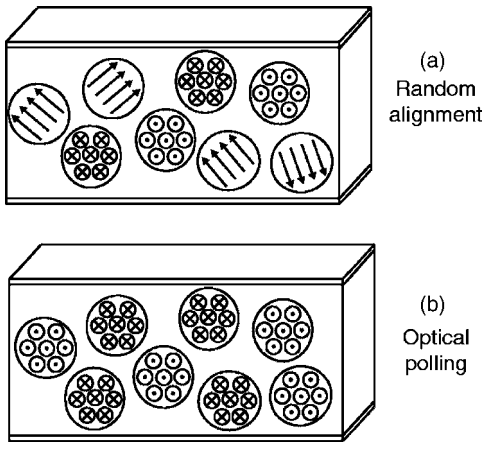

FIG. 2. Schematic diagram of liquid-crystal alignment within the droplets. With no field applied (a) the liquid-crystal directors are randomly aligned. After the polling by a polarized beam, they are optically aligned into the direction parallel to the cell surface (b).

To demonstrate this principle, four cells were manufactured with varying ratios of liquid-crystal/polymer mixture.[15] Durable structures could be written at 0%, 10%, and 24% concentrations of liquid-crystal doping with the 30% sample being unstable and unable to be used. To achieve optical tuning, the durable structures were placed in the beam path of a HeNe laser (632.8 nm) of power 30 mW and the laser was continuously scanned across the structure in a two-dimensional raster fashion, in increments of 15 min. The IR spectrum of optically polled structures was then measured with a Nicolet Nexus Fourier transform infrared (FTIR) spectrometer with Continuum infrared microscope to analyze the spectral throughput of the crystal in the stacking direction.[15] The unpolarized infrared light from the spectrometer has no effect on the alignment of the liquid crystals.

As expected, the sample with 0% liquid-crystal doping showed no variation in position of the band gap after the structure was illuminated with the HeNe laser. Figure 3 demonstrates the variation of the band-gap position as the optical polling process aligns the liquid crystals. A roughly linear shift in band-gap position can be seen in both the 10% and 24% samples until a maximum number of liquid crystals participate in the alignment process. The 10% sample sees a maximum wavelength shift of approximately 30 nm and the 24% sample provides a 65 nm wavelength shift. Consistent with Bragg's equation, the band gap shifts to the longer wavelengths as the average refractive index increases.

The optical tuning method described in this letter can be combined with the electrical tuning method based on applying a direct voltage onto the electrodes on either side of the cell.[15] Figure 4 shows the results of this combined process where the position of the band gap was first shifted optically to a longer wavelength [Fig. 4(a)] and then brought back again with the application of a voltage to the cell [Fig. 4(b)]. This method of optical and electrical tuning allows the band gap to be swept back and forth over a 65 nm region with optical polling seeing the band gap shift to longer wavelengths, and electrical tuning shifting it back to the shorter

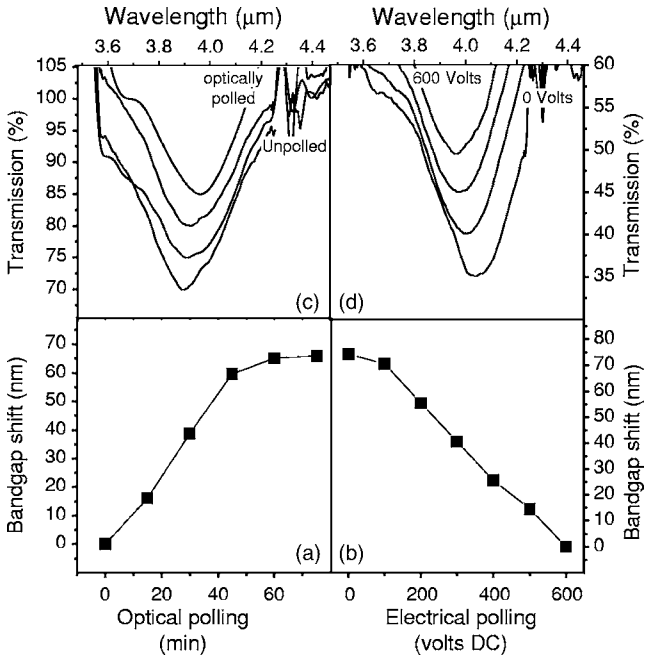

FIG. 4. The band-gap shift as a function of the optical polling (a) and electrical polling (b) processes for the 24% sample. The stop gap position shifts to shorter or longer wavelengths with the application of an optical field or an electrical field, respectively. The transmission spectra corresponding to (a) and (b) are given in (c) and (d).

wavelengths. Figures 4(c) and 4(d) show the FTIR spectra of this tuning process.

In conclusion, we have demonstrated that the 3D void channel woodpile photonic crystal generated in PDLC can be optically tuned by using a low-power polarized beam with an extinction of transmission of 70% for a 20 layer structure. The dependence of the band gap shift on the liquid-crystal doping concentration has been investigated. The combination of this optical tuning method with electrical tuning results in a tuning range in the order of 65 nm optically shifting the band gap to longer wavelengths and electrically shifting the gap to shorter wavelengths.

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