Spatial and electrical switching of defect modes in a photonic bandgap device with a polymer-dispersed liquid crystal defect layer

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Abstract: This paper investigates the spectral properties of a one-dimensional photonic crystal (PC) containing an inhomogeneous polymer-dispersed liquid crystal (PDLC) as a defect layer. Experimental results indicate that the voltage-induced reorientation of LC molecules between the light-scattering and transparent states in the PDLC enables the electrical tuning of the transmittance of defect-mode peaks in the spectrum of the PC/PDLC cell. Specifically, owing to the unique configuration of the spatial distribution of LC droplet sizes in the defect layer, a concept concerning the spatial switching in the wavelength of defect modes is proposed. As a result, the PC/PDLC hybrid cell is suggested as a potential element for realizing an electrically tunable and spatially switchable photonic bandgap device, which is polarizer-free and requires no alignment layers in the fabrication process.

OCIS codes: (230.3720) Liquid-crystal devices; (230.5298) Photonic crystals.

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1. Introduction

Photonic crystals (PCs) are known for their alluring property of the photonic bandgap (PBG) characterized by the periodic modulation of refractive index in designated structures [1,2]. Since the transport behavior of photons in the PBG is analogous to that of electrons in the energy bandgap of semiconductors, PCs have drawn considerable attention from the point of view of practical applications in electronic and optical devices [3,4]. Being part of recent development of PC structures, a variety of hybrid designs incorporating liquid crystals (LCs) as defect layers in one-dimensional (1-D) PCs have been demonstrated extensively since 2002. In such structures, distinctive features on tunable spectral profiles of defect modes can be obtained in the PBGs based on the operation principle of various LC modes. For instance, inserting an electrically-controlled-birefringence or twisted-nematic LC as the defect layer enables the electrical tunability in wavelength of defect modes in a 1-D PC/LC cell due to the change in optical path length with the applied electric field [5,6]. Similarly, other approaches, such as applying magnetic fields [7,8] or varying the incident angle of light [9] and temperature [10] to adjust the optical anisotropy of LCs, have also been proposed for realizing tunable 1-D PC/LC cells. Moreover, it has successively been confirmed that hybrid 1-D PCs in conjunction with memory-enabling LC modes not only exhibit the electrical tunability in transmittance but possess two or three sets of defect modes with memorable optical profiles [11–13].

In this study, we demonstrate an electrically tunable and spatially switchable 1-D PC/LC hybrid cell comprising an inhomogeneous polymer-dispersed liquid crystal (PDLC). The inhomogeneous PDLC consists of LC droplets with a spatial size distribution embedded in a polymer matrix. One important characteristic of the inhomogeneous PDLC is the simple electrode design for varying (say, gradient) optical properties in a uniform electric field applied to the cell. According to Ren and Wu with the purpose toward the design of tunable LC lenses [14], the LC droplets can be formed in nanometer scale and the spatial change of the droplets can thus result in gradient refractive index with parabolic profiles. In contrast, the PDLC layer investigated in this work was created to embed micrometer-sized LC droplets. As such the incident light passing through the PC/PDLC cell in the voltage-off state is highly scattered in the whole visible region and is independent of polarization, gradually becoming transmittable with increasing voltages applied to the cell. The dynamic switching between the scattering and transparent states in the PC/PDLC cell permits the realization of electrically tunable transmittance of defect-mode peaks. Specifically compared with all known PC/LC hybrids proposed previously, the spectrum of the defect modes reported in this study is not only electrically tunable but spatially switchable owing to the unique configuration of spatial micro-size distribution of LC droplets formed in the defect layer.

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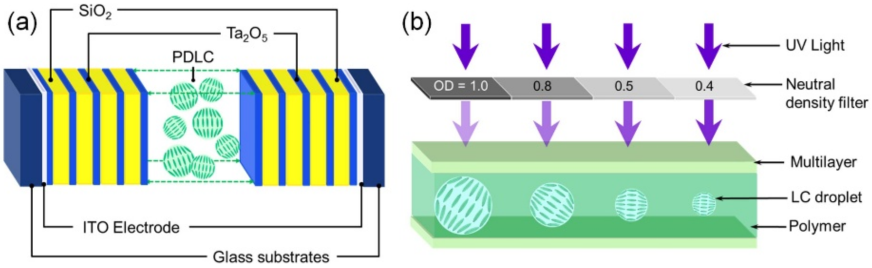

Fig. 1. Schematics of (a) the configuration of the 1-D PC/PDLC cell and (b) the setup of UV exposure for fabrication of the inhomogeneous PDLC layer.

2. Experimental

The 1-D PC/LC cell under investigation was made of an inhomogeneous PDLC serving as a defect layer sandwiched between two identical multilayers as shown in Fig. 1(a). Each multilayer is composed of five layers of Ta_2O_5 (refractive index $n_H = 2.18$ and layer thickness $d_H = 68.09$ nm) and four layers of SiO_2 ($n_L = 1.47$, $d_L = 102.37$ nm) deposited alternately on a 1.1 mm-thick glass substrate covered with an indium–tin-oxide electrode. The resulting multilayer possesses a PBG with a central wavelength of nearly 600 nm and bandwidth of 280 nm in the spectrum [15]. Two such substrates were assembled as a cell, leaving an air gap d of 4.6 ± 0.5 μm by means of ball spacers. Note that none of alignment layer was coated on the multilayer. To prepare an inhomogeneous PDLC defect layer, a nematic LC (E7, Merck; $n_e = 1.747$, $n_o = 1.522$ at the wavelength of 589.3 nm and temperature of 20 °C) was mixed with a UV-curable prepolymer (NOA65, Norland). In order to obtain a lower operation voltage, the weight percentages of E7 and NOA65 were chosen at 75% and 25%, respectively, so the resulting LC droplets are of the order of micrometer scale. The index of refraction of polymerized NOA65, n_p, is 1.524, which is comparable to the ordinary refractive index of E7. The E7/NOA65 mixture was injected into an empty cell and then exposed to ultraviolet (UV) light for photopolymerization-induced phase separation [16]. To spatially vary the LC droplet size in the PDLC, a linear-stepped neutral density filter (Thorlabs NDL-10S-4) was placed between the UV lamp and the sample. As illustrated in Fig. 1(b), the cell is divided into four zones corresponding to the optical densities (ODs) of 1.0, 0.8, 0.5, and 0.4 (from one edge to the opposite edge). The intensity of UV light before the density filter is 20 mW/cm^2 at wavelength of 365 nm and the exposure time is 30 min at room temperature. Because the LC droplet size decreases with increasing intensity of UV light, the resulting PDLC layer created under abovementioned circumstance showed a spatial LC-droplet-size distribution in the order of micrometers. All measurements were performed at room temperature without employment of any polarizer. The transmission spectra of the PC/PDLC cell in the four designated zones (Fig. 1(b)) were measured using a high-speed fiber-optic spectrometer (Ocean Optics HR2000 +) along with a halogen light source (Ocean Optics HL2000). Supplied by an arbitrary function generator (Tektronix AFG-3022B), a square-wave voltage at 1 kHz was applied to the PC/PDLC cell to induce the reorientation of LC molecules.

3. Results and discussion

Figure 2 shows the transmission spectra of the inhomogeneous PC/PDLC cell at four distinct positions under the application of various external voltages (V). For a PDLC cell with micro-scale LC droplets, the incident light transmitted through the cell is scattered in the entire visible spectrum due to the mismatch of refractive indices at LC droplet–polymer interfaces. For our proposed PC/PDLC structure, the cell operates in the light-scattering mode as $V \leq 3$ V. Noticeably, the highest strength of light scattering in each designated zone occurs at $V = 3$ V rather than 0 V. This result can be explained by the dual droplet-size and interference effects, which have previously been confirmed in PDLC cells with a higher content of LCs

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[17,18]. In the wavelength range between 400 and 450 nm near the band edge, the average transmittance of the cell decreased from 37.2 to 26.8% as the position shifts from OD = 1.0 to 0.4. This indicates that the PC/PDLC cell has a spatial size distribution of LC droplets, whose size gets smaller with decreasing OD condition. By varying the voltage to $V = 10$ V, a certain number of defect modes are resolved with pronounced transmission in the PBG, as shown in Fig. 2(a). It is clear from Fig. 2(a) that the inhomogeneous PC/PDLC cell at each position can serve as a multichannel light shutter controlled by an applied voltage between $V = 3$ and 10 V. Note that the contrast ratio between the translucent (i.e., scattering) and transparent states in the PC/PDLC can be increased by forming smaller LC droplets to enhance the light-scattering strength. As $V > 10$ V, the spectral profile of each defect mode exhibited two resolvable peaks except for the zone of OD = 0.4. In addition, the wavelength of one of the twin peaks in defect modes at $V = 40$ V nearly overlapped with that of defect modes at $V = 0$ V, as depicted in Fig. 2(b). In a PDLC cell, the LC droplets with an unavoidable variation in size are distributed randomly in the polymer matrix. Therefore, the optical path length (OPL) for the normally incident light passing through the PDLC cell in the transparent state can be written as: $\mathrm{OPL}_{\mathrm{PDLC}} = n_{\mathrm{LC}}d_{\mathrm{LC}} + n_{\mathrm{p}}d_{\mathrm{p}}$, where n_{LC} is the effective refractive index of the LC and is a function of applied voltage. d_{LC} and d_{p} represent the total path length of a light ray passing through the LC droplets and polymer matrix, respectively.

In the case of OD = 1.0 where the area is full of the largest droplets among the four designated positions, inevitable variation in droplet size is visible as shown in Fig. 3(a). It is hence reasonable to interpret that the observed twin peaks in a defect mode at a voltage higher than 10 V are attributable to the light rays going through the cell with difference in the ratio of $n_{\mathrm{LC}}d_{\mathrm{LC}}$ to $n_{\mathrm{p}}d_{\mathrm{p}}$. In addition, since the light is transmitted through the PC/PDLC cell under the condition of index match, the portion of defect-mode overlapping at $V = 0$ and 40 V is presumably caused by the light rays encountering the OPL equaling to the addition of $n_{\mathrm{o}}d_{\mathrm{LC}}$ and $n_{\mathrm{p}}d_{\mathrm{p}}$. On the contrary, the zone corresponding to the condition of OD = 0.4 exhibited a macroscopically uniform droplet size because the LC droplets are comparatively and comparably small, as shown in Fig. 3(b). As a consequence, the OPLs for all light rays are nearly identical, allowing each defect mode to have a single peak in the transmittance spectrum.

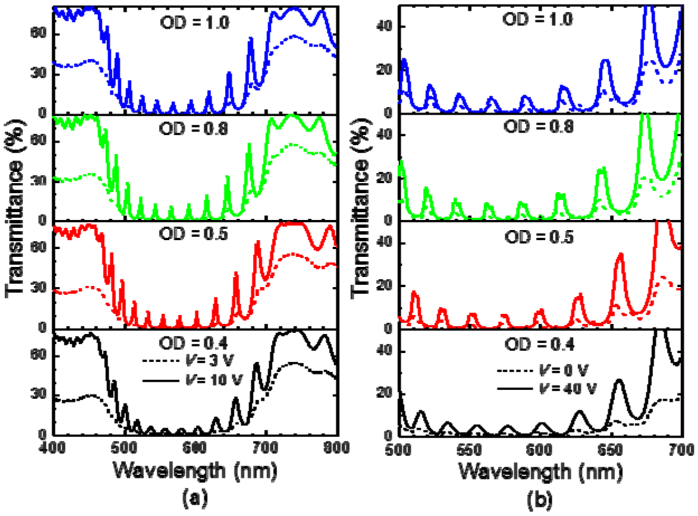

Fig. 2. Transmission spectra of the PC/inhomogeneous PDLC cell at specific positions with applied voltages of (a) $V = 3$ and 10 V, and (b) $V = 0$ and 40 V.

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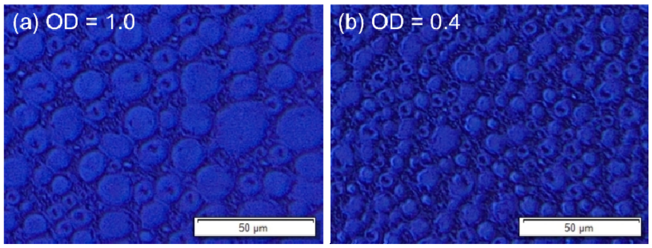

Fig. 3. Micrographs of the inhomogeneous PC/PDLC cell under a single polarizer at the positions corresponding to (a) OD = 1.0, and (b) OD = 0.4.

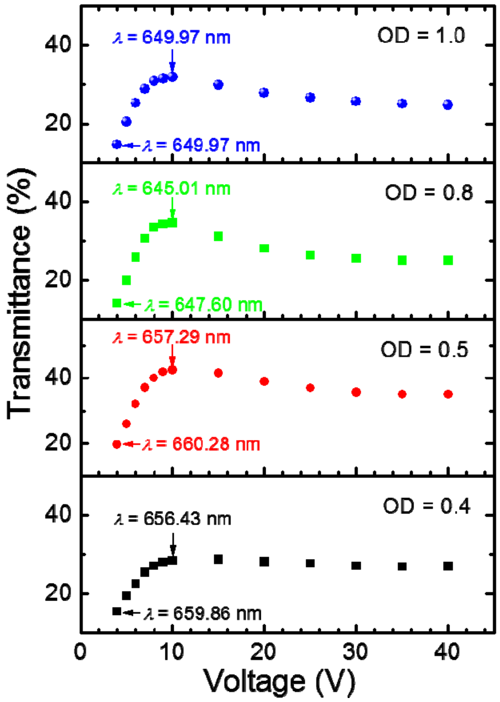

Fig. 4. Voltage dependence of transmittance of four specific defect modes in the PC/PDLC cell at four different positions.

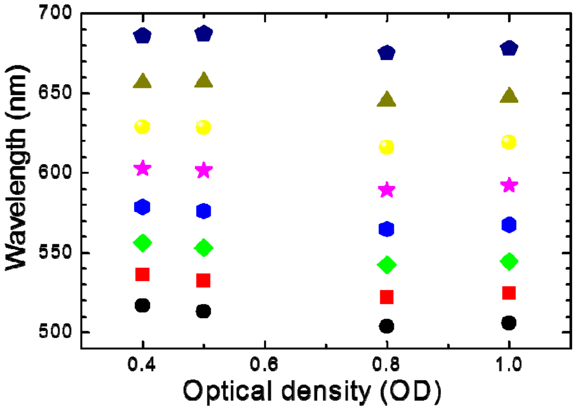

Fig. 5. Wavelengths of sets of defect modes at various sample positions of the inhomogeneous PC/PDLC cell at $V = 10$ V.

Figure 4 shows the behavior of electrical tunability in transmittance of four specific defect modes in the four given zones of the PC/PDLC cell. The changes in transmittance as well as in wavelength of a given defect mode are “irregular” in that the light is strongly scattered by the PDLC layer at applied voltages ranging from 0 to 3 V. In the voltage regime between 4 and 10 V, one can see that, accompanied by a very limited blueshift, the transmittance of each defect mode increases with increasing applied voltage. The maximum variation in wavelength for a specific defect mode is merely 3 nm, which is even smaller than the full width at half maximum (FWHM) of the defect modes (~5 nm). This suggests that the PC/PDLC cell allowing the realization of transmittance tunability of defect-mode peaks is of potential for designing an intensity-only modulator. As the applied voltage becomes higher (i.e., $V > 10$ V), the values of transmittance of the hybrid cell, at the positions of OD = 0.5, 0.8, and 1.0, decrease with increasing voltage while the transmittance remains nearly constant at the position of OD = 0.4. It has been reported that the PDLC cell with micro-size LC droplets has residual phase retardation at high operation voltages [19]. Therefore, the observed decrease in transmittance at higher voltages (i.e., $V > 10$ V in this study) can be attributed to the decrease in n_{LC} ($\approx n_{\mathrm{o}}$), which also causes the slight blueshift of defect modes.

Figure 5 demonstrates the idea of spatial switchability of defect-mode windows for the inhomogeneous PC/PDLC cell upon the application of a fixed voltage of $V = 10$ V. While the spectral profile in the PBG of the hybrid cell is dominated by a set of defect-mode peaks in each sample zone corresponding to a specific OD condition, distinct sets of defect modes shifting by approximately 10 nm in wavelength can be achieved by spatially adjusting the position for the impinging light. This is made possible by the spatial variation in effective refractive index and, in turn, the total OPL, due to the droplet-size-dependent driving voltage in association with the existing spatial size distribution in the inhomogeneous PDLC cell. Accordingly, it is implied that the resolution between two sets of defect modes in the hybrid cell can be promoted by increasing the difference in droplet size between two designated zones.

4. Conclusions

In conclusion, we have proposed and demonstrated a hybrid photonic structure with spatially and electrically tunable transmission properties by infiltrating an inhomogeneous PDLC as the defect layer in a 1-D PC. The inhomogeneous PDLC with spatially varying LC droplet sizes was fabricated with a linear-stepped density filter between the cell and UV light source during photopolymerization. For the incident light propagated through a given zone of the PC/PDLC cell, the electrical switching of LC molecules between the scattering and transparent states allows the switching of the defect modes. Controlling the strength of the applied voltage enables the modulation in transmission level of defect modes with trivial shift in wavelength (3 nm in comparison with the FWHM of *ca*. 5 nm), indicating excellent performance for realizing intensity-only modulation without any polarizers. In addition to the well-investigated characteristic of electrical tunability, as compared with other known PC/LC structures, the inhomogeneous PC/PDLC further reveals the feature of spatially tunable wavelength of defect modes. With the superior mechanical stability and morphological flexibility of formed polymers, which offers an opportunity to design flexible modulators and allows PDLC to glue the substrates by itself, the inhomogeneous PC/LC-polymer structure discussed in this work is potentially advantageous as flexible multichannel filters and modulators characterized by electrical tunability and spatial switchability once flexible substrates are implemented.

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