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Switching of Defect Modes in a Photonic Structure with a Tristable Smectic-A Liquid Crystal

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A one-dimensional (1D) photonic crystal (PC) optical device based on smectic-A (SmA) liquid crystal (LC) as a defect layer is proposed. The reversible tristability of the SmA LC is used to realize a low-energy-consumption device. With a voltage-induced scattering state, the PC–SmA hybrid cell can work as a polarizer-free optical switch. The variation of the effective refractive index of the LC substance enables the defect modes to appear at variable wavelengths, changing with the voltage-induced reorientation of the LC director. As a result, an electrically and thermally tunable multichannel optical device is achieved using this hybrid, optically tristable structure. © 2012 The Japan Society of Applied Physics

Owing to the intriguing features of photonic crystals (PCs), which exhibit a photonic band gap (PBG) forbidding photons in a certain energy range from transmitting through the periodic structure, relevant research has attracted much attention since 1987.^{1,2)} For a one-dimensional (1D) dielectric multilayer PC, the central reflective wavelength of the PBG can directly be determined via design of the optical thicknesses of the layers within the alternating stack, which can be as simple as setting each layer thickness equal to one-quarter of the central reflective wavelength. Introducing a defect layer into the PC destroys the periodic variation of the refractive index and leads to peaks of high transmission within the PBG known as the defect modes. Building on this phenomenon, a 1D electrically tunable device based on nematic liquid crystal (LC) as a defect layer was first proposed by Ozaki *et al.*³⁾ Recently, Zyryanov *et al.* have investigated the spectral properties of a PC–LC device with crossed polarizers.^{4,5)} Moreover, a 1D PC infiltrated with a twisted-nematic LC was studied both experimentally and computationally.^{6,7)} In consideration of the green concept, Wu *et al.* developed a tunable, bifunctional, 1D PC device using a bistable chiral tilted homeotropic nematic LC as a defect layer.⁸⁾ In brief, these optical structures are beneficial, which can be applied to localizing the wavelength of light.

For the purpose of creating low-power-consumption devices, the bistable characteristics of special types of LCs such as cholesteric and smectic LCs are of intense interest. An electrically controlled bistable device based on a smectic A (SmA) LC was first proposed in 1978.^{9,10)} Its highly stable scattering texture can be written and erased by applying voltage at 1 and 100 kHz, respectively. In this work, we demonstrate an optical device based on a 1D PC–SmA hybrid structure showing tunability of the optical properties via state transition among the planar (P) state, homeotropic (H) state, and the scattering (S) state by applying and removing voltage along with temperature control. Both temperature and voltage dependences of the scattering intensity are brought to light. Previous research has shown that the voltage-induced “opaque” state of SmA materials with an ionic additive can be achieved and erased by applying low- and high-frequency voltages, respectively.¹¹⁾ In our case, the S state was induced without any dopant but by force competition between the smectic

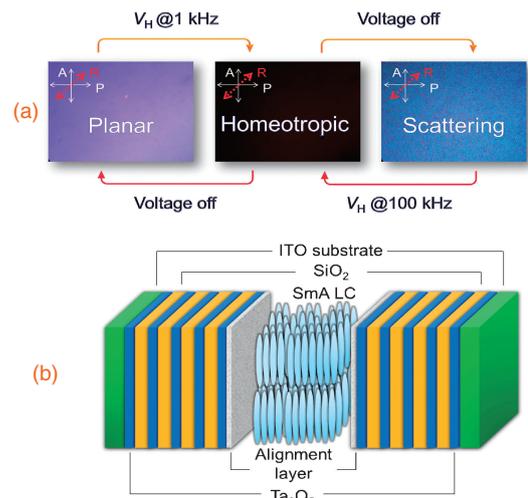


Fig. 1. (a) Microscopy images of a 1D PC–SmA hybrid cell in the P, H, and S states under crossed polarizers at 29 °C. V_H denotes a sufficient voltage that can induce the H state. The arrows indicate the transmission axes of the polarizer (P) and analyzer (A) as well as the rubbing direction (R). (b) A schematic of the hybrid cell.

layering in favor of the H state and surface anchoring to impose the P state through the state transition, resulting in random LC molecular alignment.¹²⁾ Figure 1(a) depicts the reversible drive scheme and the micrographs corresponding to the above-mentioned three states under a polarizing optical microscope. V_H denotes a sufficient voltage that can induce the H state. Note that the blue tone of the photographs is attributable to the high transmittance of the PC substrates in the blue spectral region. The S state, which can remain for many months at zero voltage, is obtained by applying a low-frequency (say, 1 kHz) voltage pulse with sufficient amplitude to overcome the anchoring energy associated with the planar alignment layer of the cell at a fixed surrounding temperature range (say, 25–30 °C). After removal of the low-frequency voltage, the competition between the anchoring energy and homeotropic inertia of LC molecules brings about random-domain alignments, thus yielding the S state. In order to increase the cell temperature to destroy the smectic layer structure, applying a high-frequency (say, 100 kHz) voltage pulse can supply considerable joule heat and, in turn, bring the optically stable P state back through a rapid thermal disturbance of the LC molecules followed by natural cooling of the material after the voltage pulse is removed. If the low- or high-frequency

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voltage is high enough and the temperature low enough in the SmA phase, the H state is persistently achieved even without retention of the external voltage. To sum up, the cell temperature is a key factor for the switching mechanism among the three stable states.

The SmA LC adopted in this study is known as 8CB with a phase sequence of Cr 21 °C SmA 33.5 °C N 40.5 °C Is. The LC was heated to the isotropic phase (above the clearing point) and then infiltrated by capillary action into two different types of antiparallel planar-alignment cells, namely, indium–tin-oxide (ITO) glass cells with a cell gap of 6 μm for fabricating typical LC cells and multilayer-coated ITO glass cells having a gap of 3 μm for the fabrication of PC–SmA hybrid cells. The dielectric multilayer deposited on each ITO substrate was composed of five alternately stacked layers of Ta₂O₅ (refractive index $n_H = 2.18$ and layer thickness $d_H = 68.09$ nm) separated by four identical layers of SiO₂ ($n_L = 1.47$, $d_L = 102.37$ nm). The resulting PBG in wavelength was from 470 to 740 nm.⁸⁾ A complete schematic of the 1D PC–SmA hybrid cell is shown in Fig. 1(b). All the voltage pulses in square waveform were supplied by a function generator (Tektronix AFG3022B) and amplified 50 times by an amplifier (TREK Model 603). For spectrum measurement of either the LC or hybrid cell, a high-speed fiber-optic spectrometer (Ocean Optics HR2000+) was employed in conjunction with a halogen light source (Ocean Optics HL2000). An oscilloscope (Tektronix TDS3034B) was used to measure the optical response time of the SmA cell when a He–Ne laser probe beam transmitted through the cell was brought to a photodetector. No polarizers were applied in the spectrum or response-time measurements. The ambient temperature was fixed by a temperature controller at 29 ± 0.3 °C unless explicitly specified.

Figure 2 displays the temperature dependence of tristable transmittance of 8CB at the wavelength of 540 nm after the removal of an agitating voltage pulse V_{H0} (~ 500 ms). Note that the symbol “ V_{H0} ” with “0” in the subscript emphasizes the state of voltage being turned off from a 1-kHz pulse initially applied to impose the H state. As shown in this figure, the variation of transmission manifests the state change of the SmA LC bulk. Owing to the smectic layering being weaker in the temperature range near the SmA–N phase transition temperature, the SmA LC bulk exhibits the optically stable P state through relaxation from the H state between 31 and 33 °C. Noticeably, below 25 °C, the SmA cell exhibits a stable H state after the removal of a 50 V pulse at 1 kHz. This suggests that the strength of the smectic layering increases with descending temperature. It is obvious that the temperature plays a crucial role in yielding a specific tristable state after the agitation of V_{H0} .

Figure 3(a) illustrates the transmission spectra of the SmA LC cell with distinct levels of scattering induced by various operating voltages at 29 °C. It is clear that the transmission intensity decreases with increasing operating voltage, implying that the orientation of the LC molecules during the initial P-to-H state transition affects the scattering intensity. Figure 3(b) reveals for the V_{H0} -dependent response time τ in the S state a power law with the exponent of 1.028 (mathematically, $\tau \approx 0.0304V_{H0}^{1.028}$) and the coefficient of determination $r^2 = 0.98$. This result is mainly due to the pretilt angle in the H state and the viscosity and elastic

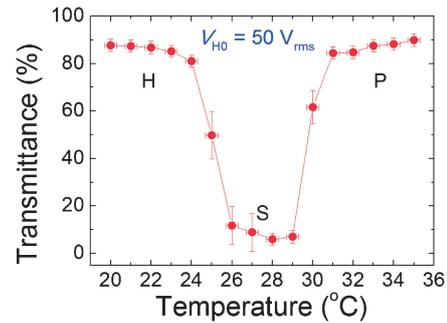
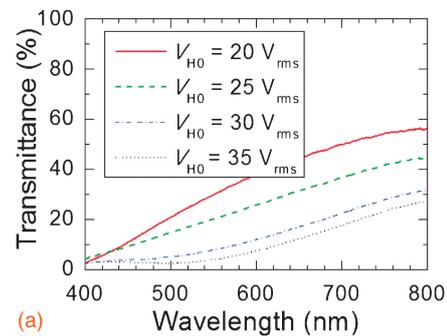
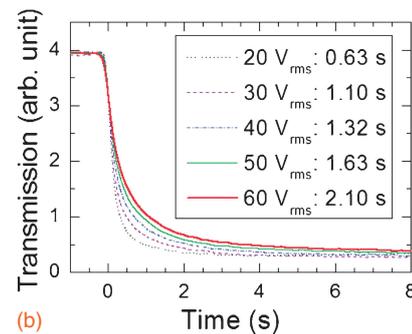


Fig. 2. Temperature-dependent transmittance at 540 nm of typical 8CB cells agitated by a short voltage pulse. V_{H0} denotes the voltage pulse at 1 kHz applied across the cell to first impose the H state and then turned off for molecular relaxation. Data are averaged from a batch of five similar samples.



(a)



(b)

Fig. 3. (a) Transmittance spectra and (b) light scattering responses at 633 nm of a typical 8CB cell in the S state induced by various V_{H0} .

parameter of the LC since the resulting S state is achieved by the relaxation process from the H state. It is worth mentioning that the response time can be reduced greatly by narrowing the cell gap, say, to 3 μm .

The spectral properties of the 1D PC–SmA hybrid structure are highlighted in Figs. 4–6. Figure 4 shows sets of high- and low-transmittance defect modes in the PBG corresponding to the H and S states, respectively. It is clear that this hybrid can be employed as an electrically tunable optical switch without the use of any polarizer, as has been demonstrated in a previous study where a PC containing a cholesteric LC was considered.¹³⁾ In light of Fig. 3(a), the level of scattering strength of the SmA bulk is determined by the agitating voltage pulse V_{H0} . The transmittance of defect modes of the PC–SmA cell can, thus, be controlled accordingly, as displayed in Fig. 5. Moreover, Fig. 6(a) delineates the blue shift of defect modes, from the stable P state (at 0 V_{rms}) to the voltage-sustained H state (at 70 V_{rms}),

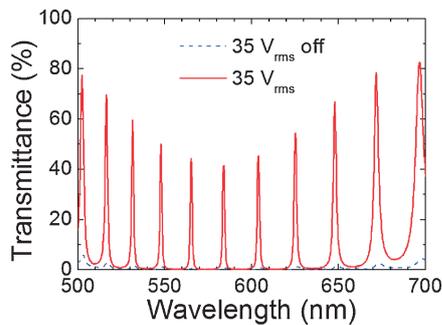


Fig. 4. Transmittance spectra of the 1D PC-SmA hybrid cell in the H and S states achieved by applying and removing a voltage of 35 V_{rms}, respectively.

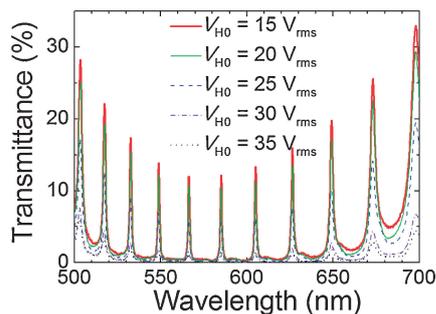


Fig. 5. Intensity-tunable defect modes of the PC-SmA hybrid cell in the PBG by various agitating voltage pulses at 1 kHz.

caused by the reduction in overall optical thickness due to the changing orientation of LC molecules with applied voltage. Note that the defect-mode doublets in the middle of the PBG are attributed to mixed optical contributions from both the extraordinary and ordinary indices of the LC molecules.⁶⁾ The defect-mode wavelengths for the H state are surprisingly inconsistent with the wavelengths of the spikes corresponding to the ordinary component for the P state. In order to observe the individual blue shifts in both the extraordinary and ordinary components, a linear polarizer was employed to modulate the polarization direction for the extraordinary ray and ordinary ray.³⁾ Figure 6(b) reveals the blue-shift behaviors of the extraordinary as well as ordinary components under increasing applied voltage. The defect modes of the ordinary component show no shift until the voltage goes beyond the switching voltage (~ 35 V_{rms}). By contrast, the defect modes of the extraordinary component continuously shift to the shorter wavelengths with increasing voltage and start to overlap with those of the ordinary component at the switching voltage incurring the H state. We believe that the additional blue shift at high voltages arises from physical bending of the glass substrates of 1.1 mm in thickness through the electric attraction between the oppositely charged plates beyond the switching voltage. From the results of both Figs. 5 and 6, one may deduce that not only the transmittance but also the location of a defect mode in the PBG can electrically be tuned in this optical device.

In conclusion, a multichannel 1D PC-SmA device has been investigated. The temperature-dependent optical characteristic of the SmA LC (8CB) has been brought to light. The SmA LC that is free of any dopant shows a great

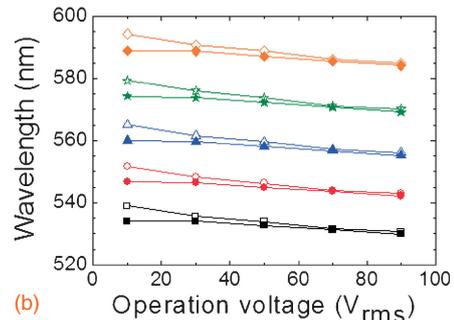
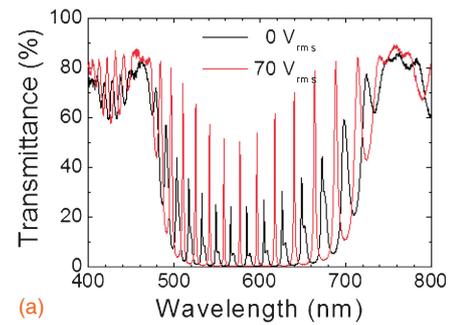


Fig. 6. (a) Transmittance spectra of the hybrid cell in the P and H states at 0 and 70 V_{rms}, respectively. (b) Defect-mode blue shift with increasing voltage for both the extraordinary (hollow symbol) and ordinary (solid symbol) components.

scattering strength with optical stability lasting for months at zero voltage and with tunability by various agitating voltage pulses to attain different orientations of the LC molecule. The resulting S state can be switched back to the other stable state, i.e., P state, through the SmA-N phase transition followed by N-SmA cooling. By taking advantage of the distinctive characteristics of 8CB to pair with the unique spectral properties of 1D PCs, high tunability of the defect modes is realized. With a voltage to induce variation of the effective index of refraction of the defect layer, the defect modes in the PBG can be adjusted within a range of 10 nm. Besides, the defect modes can work as an intensity-tunable multichannel switch with different operating V_{H0}. This 1D PC-SmA device is characterized by optical tristability and bifunctional tunability; a green optical device without any polarizer is, therefore, proposed.

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