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Electrically switched color with polymer-stabilized blue-phase liquid crystals

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We report an electrical-field switched color device using a polymer-stabilized blue-phase (PSBP) liquid crystal in which the Bragg-reflected color of the blue phase (BP) can be switched to reflect a second color. The phase-separated three-dimensional polymer network transcribes the cubic structure of a BP liquid crystal and restrains the deformation of cubic lattice by the external electric field. The new wide-range electric-field switched colors with PSBP may be an important step toward ecofriendly color reflective displays. © 2010 Optical Society of America

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The ability to tune the optical properties of liquid crystals in response to external stimuli makes them attractive materials for displays and active optical elements. Blue-phase (BP) liquid crystals are among the most interesting self-organized structures in the field of liquid crystals, and they have drawn numerous studies on their physical and electro-optical properties in past decades [1–5]. They are optically active and isotropic owing to the symmetry of cubic structure. Three BPs are thermally stable in a fairly short temperature range: blue phase III (BPIII), blue phase II (BP II), and blue phase I (BPI). The structure of BPIII is known as a foggy phase, BP II is a simple cubic phase, and BPI is a body-centered cubic phase [1]. Recently, broadening in the temperature range of a BP liquid crystal by using a mixture of nematic bimesogenic liquid crystals [6] or by polymerizing a small amount of monomer in a BP to stabilize the cubic lattice [7] against the temperature variation has revived interest in exploiting BP liquid crystals beyond their basic scientific aspects. For example, the field-induced birefringence of BP liquid crystals, known as the Kerr effect [8], has found its footage in practical applications because of its broad BP temperature and fast electro-optical response time.

Compared with the optical Kerr effect, the electric-field induced shift in Bragg reflective wavelength, known as electrostriction, has drawn little attention owing to the short range of the switched wavelength change. Moreover, to our knowledge, electrostriction in polymer-stabilized blue phase (PSBP) has never been explored. In a prior report [7], the polymer network used to stabilize BP liquid crystals for a wider temperature range might have hindered the lattice change under electric field. To provide an energy-saving electro-optical device that works in a reflective mode, we have previously demonstrated the electrically switched color in a polymer-stabilized cholesteric liquid crystal [9]. In this study, we demonstrate PSBP with a wide tuning range of reflected wavelength, which shows the three primary colors in a single cell. Compared with polymer-stabilized cholesteric liquid crystals, PSBP provides a narrower half-bandwidth and less than one half of the driving voltage required for the electrically switched colors.

A BP liquid crystal consists of a nematic (32.36 wt. % of BL006, Merck) and a chiral dopant (63.28% of CB15, Merck), while the PSBP sample has an additional reactive mesogenic monomer (4.52% of RM 257 based on the BP liquid crystals, Merck) and a small amount of photoinitiator (0.04% of Irgacure 651 based on the BP liquid crystal, Ciba Additive) to provide a room temperature BP. The electro-optical cells are composed of rigid substrates with top-down electrodes configuration and with surface alignment layers provided for homogeneous alignment. The cell gap is kept at 10 μm using ball spacers to separate substrates. The PSBP mixture is filled into the cell at an isotropic state and cooled down to room temperature at a rate of 0.1°C/min. We observed the BP range is from 35.0°C to 26.9°C. The polymerization temperature is chosen at 29.4°C. At this temperature, the BP domains are large and in a uniform color. The microscope picture of the PSBP mixture during cooling process before polymerization is shown in Figs. 1(a)–1(e). The cell is illuminated with a UV lamp (0.4 mW/cm², 365 nm) for 40 min to polymerize the reactive monomer. After UV illumination, the PSBP cell is examined again with a polarization microscope. The texture obtained during the cooling process is presented in Figs. 1(f)–1(j). A BP range from 23.0°C to 17.0°C is observed. The BP temperature range has been shifted to a lower temperature compared with the mixture before polymerization. This is because the prepolymerizable mixture with a mesogenic monomer returns to the original BP liquid-crystal formulation after the phase separation of polymer network. For comparison, a separate cell is filled with the BP liquid crystal without the polymer, in which the BP range is tuned at a similar range by having the same ratio of nematic to chiral dopant. The reflection spectra are determined with an Ocean Optics spectrometer at room temperature.

Application of an electric field across BP materials in an electro-optical cell can induce a small shift in Bragg-reflected wavelength at a low applied voltage. The electric field interacts with the local dielectric anisotropy of a blue phase. The distorted lattice re-
results in the change of spectral reflection peak as graphically illustrated in Fig. 2. This electric-field-induced mechanical effect is named as electrostriction, where the distortion can be described as the strain tensor $u = RE^2$, where $u$ is the resulting strain, $R$ is the electrostriction coefficient, and $E$ is the electric field [10].

A wider switching range in reflected wavelength has been observed in the PSBP cell. By comparing the cells with pure BP material and PSBP, the incorporation of polymer in a BP liquid crystal helps in the stabilization of the BP structure in response to the application of an electric field. In Fig. 2(a), the applied voltage is limited under 30 V. As the electric field goes higher, the BP structure will be switched to focal conic texture, which is not in the scope of our study. There is a discontinuous region of tunable wavelength in the case of the PSBP cell, as indicated in Fig. 2(b). As a voltage of 30 V is applied, a second peak at 510 nm starts growing. We believe this is an electrically induced phase transition between BP I and BP II. A hysteresis of tunable wavelength is observed between 470 nm and 530 nm by decreasing voltage.

A color change in response to the applied voltage of a PSBP cell can be easily observed in a single-pixel cell in which the electrode area is switched to reflect a different color while the surrounding area with no electrodes remains the original blue color [Figs. 3(a′)–3(c′)]. The incorporation of a small amount of polymer network stabilizes against the occurrence of lattice deformation and broadens the range of electrically switched color in the visible spectrum.

Both the BP and PSBP cells demonstrate a redshift in the reflection spectra in response to the electric field. The half-bandwidth is around 30 nm, which provides a good color chromaticity in comparison with the cholesteric Bragg reflection band (∼85 nm). The electric-field switched color is reversible with continuously ramping upward and downward in applied electric field. In general, there is a trend show-
ing reflectivity at the short wavelength region, which is higher than that of the switched colors at the long wavelength region. By comparing the two cells, a wider tunable color range is achieved by the PSBP cell. In the case of a BP liquid-crystal cell, Fig. 2(a), the range of switched color is around 50 nm. By contrast, the counterpart PSBP cell shows that the range of switched color is nearly the full visible spectrum.

To confirm that polymer network enhances the cubic lattice structure in response to the electro-mechanical deformation, we carried out the morphological study of the sample by extracting BP liquid crystals from the cell with hexane. The cell is opened, and the polymer is sputtered with a thin layer of gold and examined with a scanning electron microscope (SEM). As a result, the SEM images [Figs. 4(a) and 4(b)] reveal that the polymer network showing a water lilylike structure connected to both substrate surfaces between mimics the periodic structure of a cubic-lattice pattern from a cell without a surface alignment layer. In contrast, the phase-separated mesogenic polymer network forms dried seed podlike structure of a lotus with thin and interconnected polymer ribbons of around 0.6 μm in width interconnected holes that vary in size and distribution, and (d) the enlarged image of the spongelike polymer morphology.

To conclude, we have demonstrated electrically-switched color reflective device using a polymer stabilized liquid-crystal BP mode. Compared with the cell with only BP liquid crystals, the PSBP cell enables a wider tuning range up to 160 nm at applied voltage of 40 V for a 10 μm cell. The nature of the device working in a reflective mode does not require a backlight system, color filters, and polarizers. The color generation without color filters and polarizers with a reflectivity up to 40% with respect to the incident light is possible. It also requires a relative low driving voltage compared with the PS cholesteric liquid crystals [9]. This reflective electrically switchable color device may find wide range applications in information displays.

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