IEEE Photonics Journal
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Volume 8, Number 6, December 2016

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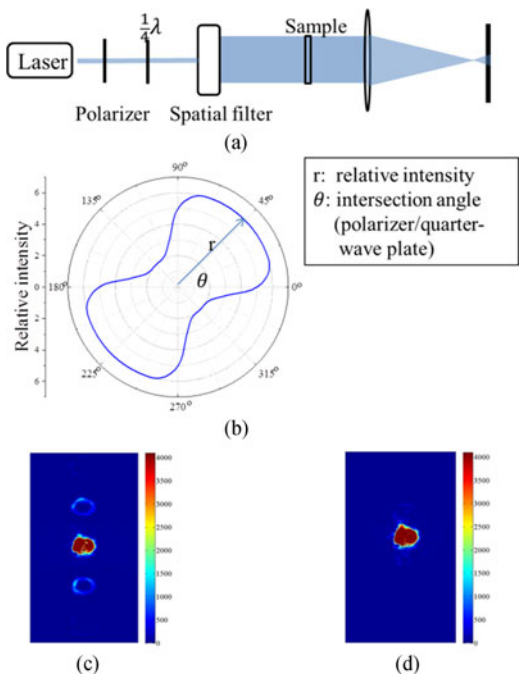

DOI: 10.1109/JPHOT.2016.2623671
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Optically Switchable Circularly Polarization-Dependent Optical Vortex

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DOI:10.1109/JPHOT.2016.2623671
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Manuscript received September 18, 2016; revised October 26, 2016; accepted October 28, 2016. Date of publication November 1, 2016; date of current version November 14, 2016. This work was supported in part by the Natural National Science Foundation of China under Grant 61405088 and Grant 11574130 and in part by the Shenzhen Science and Technology Innovation Council under Grant JCYJ20150601155130435, Grant JCYJ20160226192528793, Grant JCYJ20150930160634263, and Grant KQTD2015071710313656. Corresponding author: D. Luo (e-mail: luo.d@sustc.edu.cn).

Abstract: An optical vortex, which consists of blue phase and isotropic phase, is generated from azobenzene liquid crystal cell with computer generated hologram pattern. This device is optically switchable and can be erased and generated by ultraviolet or green light, respectively. An intensity modulation is formed between blue phase and isotropic phase of liquid crystal cell, where the blue phase liquid crystal selectively reflects circular polarization light due to the Bragg reflection, resulting in a circularly polarization-dependent optical vortex. The proposed method can be applied to any other diffractive optical elements.

Index Terms: Polarization-dependent, optical vortex, azobenzene liquid crystal.

1. Introduction

The optical vortex (OV) is a topological point defect on a wavefront and manifested as a null within a light beam, where the phase at the defect point is in determination [1], [2]. Considerable attention has been paid to OV owing to its special application such as rotational frequency shift [3], [4], optical trapping [5], [6], and optical manipulation for microelectromechanical systems [7]. Optical method containing an angular phase can create OV beam through many approaches such as spiral phase plate [8], computer generated hologram [9], phase masks [10] and mode converters [11]. The blue phase is a special mesophase existing between the isotropic and chiral nematic phase of liquid crystals (LCs). It attracts enormous interests due to its advanced properties such as no birefringence, selective Bragg reflection and fast response time. For the polarization of Bragg reflection, the blue phase induced is related to LC molecular orientation, which is determined by chiral dopant; for instance, R-chiral dopant doped LC can only reflect dextrorotatory light [12].

Azobenzene is a kind of material that can change its molecular structure under ultraviolet light (UV) and green light between trans *isomer* and *cis* isomer, which has been used for phase transition between blue phase and chiral nematic phase [13], [14], and spectra shift [15]–[19]. Optical switch mechanisms, such as phase transition between blue phase and chiral nematic phase of azobenzene materials, have been explored intensively based on azobenzene materials including azobenzene chiral dopant [16], [17], azobenzene liquid crystal [15], [20]–[22], and other azobenzene molecules

[13], [14], [18], [19]. Recently, photo-manipulated photonic bandgap devices based on optically tristable chiral-tilted homeotropic nematic liquid crystal has been demonstrated [23]. However, the studies on switchable optical devices based on isotropic phase and blue phase doped with azobenzene liquid crystals are rarely reported.

In this paper, an optical switchable optical vortex was generated from liquid crystal cell with computer generated hologram (CGH) pattern, which consisted of isotropic phase and blue phase liquid crystals (BPLCs). This device is optically switchable and can be erased and generated by ultraviolet or green light, respectively. In our proposed method, the device can be transformed among chiral-nematic phase, blue phase, and isotropic phase through optical manipulation directly, without changing temperature as conventional way. An intensity modulation is formed between blue phase and isotropic phase of liquid crystal cell, where the blue phase liquid crystal selectively reflects circular polarization light due to the Bragg reflection, resulting in a circularly polarization-dependent optical vortex.

2. Experiments

Herein, a dose of azobenzene liquid crystal which can changed its molecule structure between *trans* and *cis* isomers was mixed into chiral-nematic liquid crystal to change the phases of the compounds. The changes of molecules structure will lead to phase transition through chiral-nematic phase, blue phase and isotropic phase. Before UV exposure, the azobenzene liquid crystal with *trans* isomer exhibits as an nematic liquid crystal. After UV exposure, the azobenzene liquid crystal transforms to *cis* isomer which exhibits as a kind of isotropic liquor, at the meantime, it will break some amount of double twist structure of liquid crystal that ought to be blue phase, thus decreases the clear point and the compounds, and becomes isotropic phase. The working temperature of the optical switching is controllable through the concentration of azobenzene liquid crystal doped. It can even be realized at room temperature, and has a temperature range of about 8 °C, which is a little higher than pure liquid crystal with chiral dopant due to azobenzene molecule.

In blue phase liquid crystal, the reflection is due to the selective Bragg reflection based on three-dimensional periodic structure formed by double-twisted self-assembled liquid crystal molecules. The lattice structure of blue phase is deformable in an electric field, which leads to a variation of reflection wavelength. The reflection wavelength can be expressed as

$$\lambda = \frac{2na}{\sqrt{h^2 + k^2 + l^2}}, \tag{1}$$

where a denotes lattice constant; n denotes average refractive index; and h, k, and l are the Miller indices of a crystal plane.

In this experiment, the mixture doped with azobenzene liquid crystal was prepared with liquid crystal HTG135200-100 56.5 wt% ($\Delta n = 0.2$ at $\lambda = 633$ nm, $\Delta\varepsilon = 96$ at 1 kHz and 22 °C, and clearing temperature $T_c = 95.7$ °C), R-chiral dopant R5011 3.5 wt% (HTP≈126/μm), all above is from HCCH (Jiangsu Hecheng, China), and photoisomerisation azobenzene liquid crystal 1205 40 wt% (a multi-component mesogenic material from Beam Co., USA). After mixing, the mixture was filled into a liquid crystal cell, which was formed by two pieces of glass. The cell gap was 10 μm. The prepared sample was maintained at 50 °C (chiral nematic phase) through a hot stage (HCS402, INSTEC, USA). The phase transition sequence of the LC mixture is following: It is chiral-nematic phase from room temperature to 62.5 °C, becomes blue phase in 62.5 °C to 67 °C, and finally turns to isotropic phase above 67°C.

The optical switch was realized by illuminating the azobenzene liquid crystal which can reversibly change its molecule structure between *trans* and *cis* isomers under illumination of ultraviolet (UV) light and green light. In our experiment, we can manipulate the phase transitions of sample between the chiral nematic phase, blue phase, and isotropic phase.

The transformation of azobenzene liquid crystal doped compounds from chiral nematic phase to isotropic phase can be realized by UV light exposure (100 mW) for seconds. Fig. 1 depicts the images of phase changing process of our sample, from chiral-nematic phase to isotropic phase

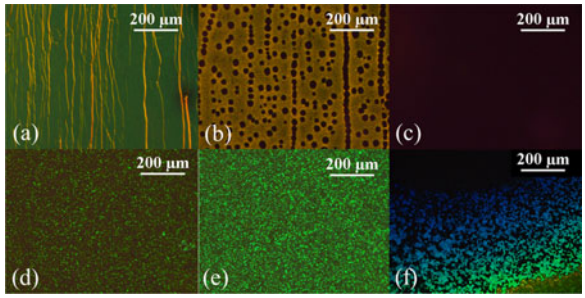

Fig. 1. Polarizing optical images of sample exposed in UV light with initial phase of chiral nematic phase: (a) before UV exposure, (b) exposed in UV light for 10 s, and (c) exposed in UV light for 20 s, (d) exposed in green light for 120 s, (e) exposed in green light for 150 s, and (f) phase transition under dark state. The scale bar represents 200 μm.

and from isotropic phase to blue phase. Optical images were observed by an optical polarization microscope. Firstly, the compounds were at chiral-nematic phase, which was a typical chiral nematic phase, as shown in Fig. 1(a). The doped azobenzene liquid crystal exhibited as nematic liquid crystal at the beginning. After UV (365 nm, 100 mW) exposure for about 10 seconds, the azobenzene liquid crystal began to transform from *trans* isomer to *cis* isomer which exhibits as a kind of isotropic liquor, thus the phase began to change to isotropic phase without increasing temperature as shown in Fig. 1(b). In other words, the transform of azobenzene liquid crystal changed the clear point of the liquid crystal compounds. After 20 seconds, the mixture finally changed to isotropic phase rather than blue phase owing to the destruction of double twist structure of mid-state that did not show up by azobenzene liquid crystal molecules. The image of isotropic is dark, as shown in Fig. 1(c). After exposure in green light (520 nm, 150 mW) for about 90 seconds, the azobenzene liquid crystal transformed from *cis* isomer to *trans* isomer, and the double twist structure began to set up, thus blue phase began to arise. The image observed by polarization optical microscope became bright with tiny green mosaic that represented blue phase, as shown in Fig. 1(d). As the cell was maintained under green light exposure for about 150 s, the brightness of blue phase further increased with more mosaic with larger sizes, the images were shown in Fig. 1(e), respectively. And the blue phase would recover to chiral nematic phase under dark state for about 30 minutes without hot stage for temperature controlling. In our experiment, we found that the phase transition between chiral nematic phase and isotropic phase, and between isotropic phase and blue phase were reversible in certain conditions such as UV/green exposure or naturally change in dark state. Only the phase transition from blue phase to chiral-nematic phase was irreversible. Meanwhile, blue phase did not appear stably while isotropic phase transforming to chiral nematic phase under dark state, for the blue phase would turn to chiral nematic phase soon as it formed. Therefore, actually what we saw was the image that blue phase and chiral nematic phase mixing together, there was no blue phase existing, as shown in Fig. 1(f).

Therefore, we can optically manipulate the phases of mixture with azobenzene liquid crystal between chiral nematic phase, isotropic phase and blue phase through UV light or green light exposure. The absorption spectrum of LC compounds is plotted in Fig. 2(a). The absorption wavebands of the compounds are ultraviolet light and blue-green light, and the data below zero in Fig. 2(a) is induced by measuring errors of the equipment. The simplified process of phase transition is illustrated in Fig. 2(b). The mixture with azobenzene liquid crystal can be transformed to isotropic phase by UV light exposure no matter it was chiral-nematic phase or blue phase at the initial state. As well, it can be transformed to chiral-nematic phase either from blue phase or from isotropic phase under dark state. However the process to achieve blue phase was irreversible, which can only be achieved from isotropic phase under green light exposure. To achieve blue phase, the liquid crystal compounds in chiral nematic phase needed to be exposed under UV light for several seconds to transform to isotropic phase, and then be exposed under green light for several minutes to achieve blue phase.

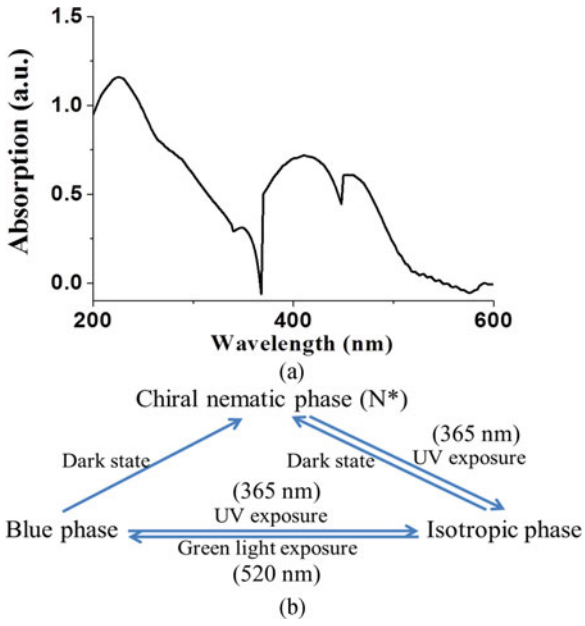

Fig. 2. (a) Absorption spectrum of the LC compounds in our experiment. (b) Schematic of phase transition between chiral nematic phase, blue phase, and isotropic phase.

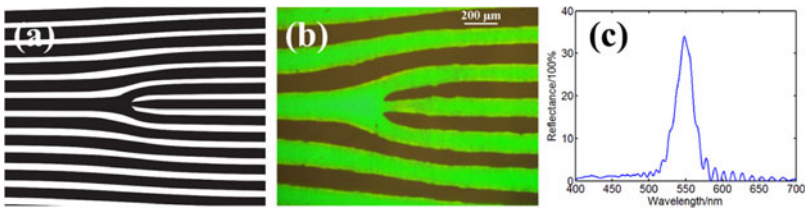

Fig. 3. (a) Computer-generated hologram used in experiment. (b) Image of liquid crystal with CGH pattern observed under polarizing optical microscope. (c) Reflection spectrum of the BP state of the LC cell.

3. Results and Discussion

As the phase transition between blue phase and isotropic phase, both with isotropic refractive index, can be controlled by optical method, an optical vortex can be realized through a LC cell with computer generated hologram (CGH) pattern. A monochromatic beam propagating in the *z*-direction and containing a single vortex transversely centered at the origin is described by following scalar envelope function [1]:

$$u(r, \theta, z) = A_m(r, z) \exp(im\theta) \exp[i\Phi_m(r, z)] \tag{2}$$

where (r, θ, z) is the cylindrical coordinates with the optical axis (z-axis), $\exp(im\theta)$ is the characteristic expression of the OV, m is a signed integer called the topological charge, and Φ_m is the phase. To generate a computer generated hologram corresponding to an OV, we calculated the interferogram of two waves including a planar reference wave and an object wave carrying on the desired optical vortex [1]. The numerically calculated CGH pattern was printed out on a transparency with a laser printer. The pattern used in our experiment is shown in Fig. 3(a), where $m = 2$. To transfer the constructed CGH pattern to LC cell, the LC cell filled with liquid crystal mixture with azobenzene liquid crystals was first turned from isotropic phase to the state of blue phase under green light exposure. Then, the transparency with CGH pattern was adhered on the LC cell, a UV light with

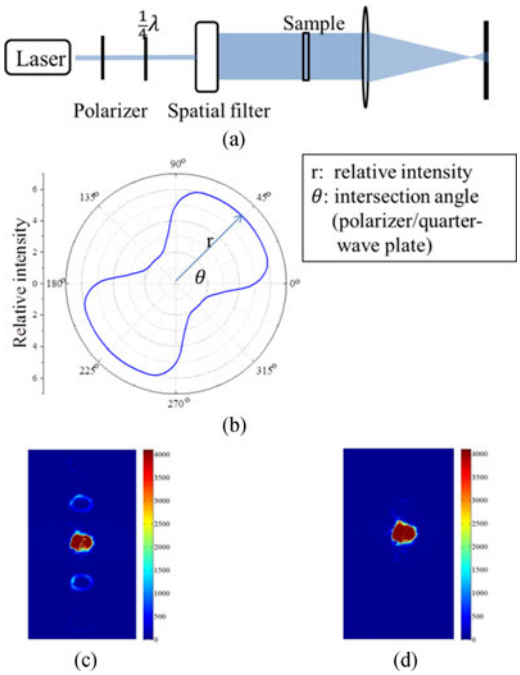

Fig. 4. (a) Experimental equipment. (b) Relative intensity of transmitted light of blue phase liquid crystal doped with right-hand chiral dopant as the function of intersection angle of polarizer and the quarter-wave plate. (c) Propagated image of vortex under dextrorotatory light. (d) Propagated image of vortex under levorotatory light.

intensity of 50 mW/cm^2 was used to expose the LC cell through the CGH pattern for about 20 s. Fig. 3(b) shows the optical image observed under optical polarization microscope, where the green region and black represents blue phase and isotropic phase, respectively. The region in black was turned from blue phase to isotropic phase, while the green region kept as the blue phase. The whole CGH pattern can be erased and generated by UV light; thus, this device was optically switchable. Fig. 3(c) exhibits the reflection spectrum of the blue phase state of the LC cell that appears in Fig. (b).

In our experiment, the optical setup for circularly-polarization-dependent optical vortex is shown in Fig. 4(a). A laser beam with wavelength of 543 nm (He-Ne laser) was firstly transformed to circularly polarized light by a polarizer and a quarter-wave-plate, and then incident on a spatial filter system with an objective lens and a pinhole. The expanded beam was then collimated and impinged on the sample. After Fourier transformation, the picture of optical vortex was captured by a charge-coupled device (CCD) camera.

As we know, the polarization of Bragg reflection of blue phase is related to LC molecular orientation which is determined by chiral dopant. For instance, LC doped with right-chiral dopant can only reflect dextrorotatory light [12]. In our experiment, the blue phase was tuned to reflect circularly polarized green light by carefully choosing the concentration of chiral dopant. It is worth noticing that, the light intensity of 543 nm used to generate the optical vortex was very weak, which wouldn't trigger the phase transition of liquid crystal mixture here. Therefore, the proposed optical vortex generated from blue phase and isotropic phase was circularly polarization dependent. Fig. 4(b) plots the relative transmitted intensity (absolute value of r) of the blue phase liquid crystal doped with right chiral dopant R5011 in our experiment, as the function of intersection angle between the polarizer and the quarter-wave plate, represented by θ (rotate the quarter wave plate, clockwise rotation is positive). When the angle θ was set to 45°, a levorotatory circularly polarized light was generated, and the reflectance of blue phase liquid crystal was minimum; thus, the transmittance was maximum. In this condition, the sample would act as an amplitude-modulation binary DOE,

where the transmittance of blue phase and isotropic phase had the largest difference, resulting in OVs ($\pm$1st order), as shown in Fig. 4(c). When the quarter-wave-plate was set to $-45°$ (or 315°), a dextrorotatory circularly polarized light was generated and the reflectance of blue phase liquid crystal was maximum; thus, the transmittance was minimum. In this condition, the transmittance of blue phase and isotropic phase had no difference, resulting in no reconstructed OV, as shown in Fig. 4(d). By rotating the quarter-wave plate, the transmittance of generated light changed, thus enables the tunability of the intensity of OV. Though the largest difference of transmittance is not high enough to induce high order diffraction, the diffraction efficiency of first order is only less than 10%. The polarization of vortex is circularly polarized. However, it is a new way to get tunable diffractive pattern. Unlike other method to get liquid crystal OV, there is no need in this way to manage an electrical system, and therefore, it has a simpler structure. In this method, many other patterns can be achieved in similar way.

Although the efficiency of our proposed device might be limited by the amplitude-modulation mechanism where parts of incident light will be reflected by the Bragg reflection of blue phase, it does provide a new method to fabricate diffractive optical element capable of optical tunability. The diffraction efficiency can be increased by coating anti-reflective film.

4. Conclusion

In conclusion, phase transition between the chiral nematic phase, blue phase, and isotropic phase through liquid crystal compound doped with azobenzene liquid crystals has been demonstrated. An optically switchable circularly polarization dependent optical vortex was generated from liquid crystal cell with computer generated hologram (CGH) pattern, which consisted of isotropic phase and blue phase liquid crystals, through optical manipulation with azobenzene liquid crystal. This device was optically switchable, and the CGH pattern can be erased and generated by UV or green light. An intensity modulation was formed between isotropic phase and blue phase, whose reflectance and transmittance depend on the polarization state of the incident light and used to generate the circularly polarization-dependent optical vortex. The proposed method can be applied to other diffractive optical elements with optical tunability.

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