



Optically switchable and axially symmetric half-wave plate based on photoaligned liquid crystal films



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ABSTRACT

We demonstrate an optically switchable half-wave plate (HWP) composed of a photoaligned and axially symmetric liquid crystal (ASLC) film containing two azobenzene derivatives, methyl red (MR) and 4-butyl-4'-methoxyazobenzene (BMAB). MR is responsible for photoalignment, and BMAB is used for optical tuning and switching the state of polarization (SOP) of probe beam (633 nm He–Ne laser) passing through the MR/BMAB doped ASLC film. The photoaligned ASLC film is first fabricated using a line-shaped laser beam (532 nm) exposure applied on a rotating LC sample. The fabricated ASLC film can passively change the linearly polarized light. Under UV light exposure, the formation of *cis*-BMAB (bend-like shape) within the film disrupts the LC molecules, switches the LC orientation, and further changes the SOP of the probe beam. Under laser irradiation (532 nm), the formation of *trans*-BMAB (rod-like shape) reverts the LC orientation back and simultaneously generates *cis*-MR, helping anchor the LC in the previously photoaligned orientation. The photoaligned MR/BMAB-doped LC HWP can change the linear SOP under alternating UV and visible light exposure.

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1. Introduction

Polarization beam splitters (PBSs) and half-wave plates (HWPs) play crucial roles in optical systems that require passive and active tuning of polarization. In active tuning of linear polarized light, a mechanical force, such as rotation [1,2], must be applied on an HWP composed of a rounded and thin-film coated glass to achieve different linear state of polarization (SOP) between *s*-polarization and *p*-polarization. To precisely and actively tune and switch polarization, a liquid crystal (LC)-based variable retarder [3–13] layered with an LC film of a twisted structure can change the SOP of incident laser light under an applied electrical field. In general, LC twisting is completed by passive LC alignment in which two or more rubbed glass substrates with parallel or perpendicular orientation are used. However, applying LC alignment by using this rubbing technique is difficult in LC-based micro- or nano-devices. Recent advances in the photoalignment of LC by using an azobenzene (Azo) derivative as a photoaligned agent enable

noncontact LC alignment without the use of rubbed glass substrates [14–22]. The deformation of Azo under light exposure aligns and anchors the LC orientation. Compared with the rubbed substrate technique, photoalignment can more efficiently achieve the submicron-scale resolution for LC alignment. The Azo derivatives not only can perform the passive photoalignment of LC, but also can actively tune and switch the LC orientation under UV and visible light illumination [23–29]. Under UV light illumination, the generation of *cis*-Azo disrupts the LC orientation and changes the LC phase from nematic to isotropic. Under visible light illumination, the LC reverts back due to the generation of *trans*-Azo. The optical properties from photoresponsive LC can be modulated under alternative UV–visible illumination.

In this study, we demonstrate an optically switchable HWP (linear retarder) composed of a photoaligned and axially symmetric LC (ASLC) film containing two Azo derivatives, methyl red (MR) and 4-butyl-4'-methoxyazobenzene (BMAB). MR is responsible for photoalignment [19], whereas BMAB [30] is used for optical tuning and switching the SOP of light passing through the ASLC film. MR is an Azo dye and commonly used as a pH indicator. Laser exposure at a wavelength of 532 nm generates the *cis*-form of MR (bend-like shape) and anchors the LC, resulting in LC photoalignment. BMAB is an LC-like Azo and undergoes reversible *trans*-*cis* photoisomerization

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under alternating UV and visible light irradiation [31]. In our MR/BMAB doped LC system, the photoaligned ASLC film is fabricated using a line-shaped laser beam (532 nm) exposure applied on a rotating LC sample. Under UV light exposure, the formation of *cis*-BMAB (bend-like shape) disrupts the LC molecules, switches the LC orientation, and further changes the SOP of the probe beam. Under laser irradiation (532 nm), the formation of *trans*-BMAB (rod-like shape) reverts the LC orientation and simultaneously generates *cis*-MR, helping anchor the LC in the previously photoaligned orientation. The photoaligned MR/BMAB-doped LC HWP can change the linear SOP between *s*-polarization and *p*-polarization under alternating UV and visible light exposure.

2. Experimental

Fig. 1 (a) shows the schematic of our optical setup used to achieve the photoalignment in ASLC films. The LCs used were a nematic LC (NLC, MDA 3461, Merck Taiwan), a blue-phase LC (BPLC, LCM- RTBP.1328VIS, LC MATTER Corp.), and a cholesteric LC (CLC) formed by a 15 wt% chiral dopant (ZLI-811, Merck) and 85% NLC. The LC samples were fabricated as followed: first, an epoxy-sealed sandwiched open cell was made by two glass substrate (rubbed or unrubbed) within a 12 μm plastic spacer. Second, a mixed LC containing Azo derivatives was mixed using mixer and sonicator and injected into the sandwiched open cell. Finally, the LC sample was kept vertical to make sure the LC diffused in the sandwiched for 10 min before the photoalignment process. A 532-nm diode-pumped solid state laser was used as the light source for photoalignment because the peak absorption of MR is nearly 532 nm. The laser beam was passed through a line mask of 200 μm wide and 8 mm long. A cylindrical lens then focused the line-shaped laser beam onto the rotating sample (4 Hz) for 30 min. The SOP of the LC sample was measured without post-treatment at room temperature. Fig. 1 (b) shows the optical setup used to measure the SOP using a He–Ne laser as probe beam. A rounded and rotational glass HWP was placed directly in front of the probe beam to ensure that the *s*-polarization to *p*-polarization was 50:50. After passing

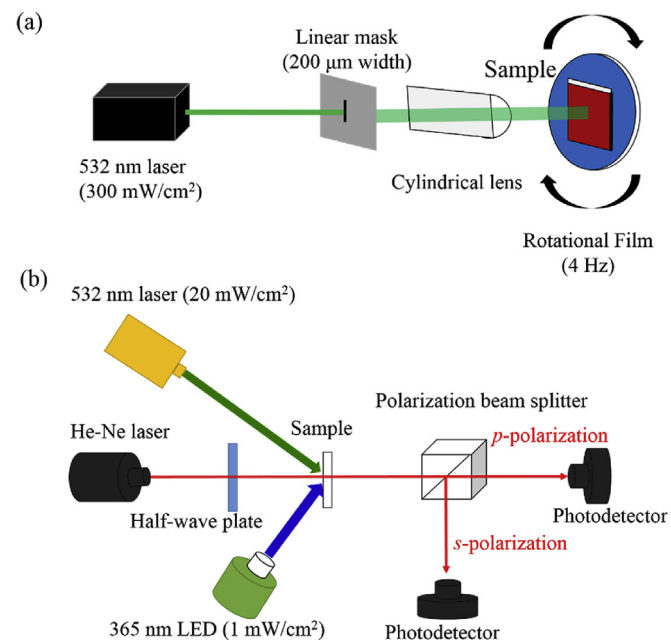


Fig. 1. Schematic of (a) fabricating a photoaligned ASLC film and (b) measuring the SOP from the LC sample under light exposure.

through the LC sample, the probe beam was separated by a PBS and the transmitted (*p*-polarization) and reflected (*s*-polarization) intensities were recorded by a photodetector, separately. Two irradiated beams, UV (peak wavelength of 365 nm) and visible (532-nm wavelength laser), alternatively illuminated the LC sample. All the measurements were performed at room temperature.

3. Results and discussion

The electrically controllable LC HWP is normally fabricated using two rubbed substrates that anchor and align the LC molecules. Here, we used two rubbed substrates of parallel orientation filled with BMAB-doped BPLC to create an optically switchable HWP. Fig. 2 shows transmittance changes based on different switching states of BMAB-doped BPLC and the corresponding switching mechanism from the LC sample. Before light irradiation (light-off state), the SOP of the sample showed 100% *p*-polarization, as shown in Fig. 2a (black circle). Because the SOP of the probe laser before passing through the BPLC was adjusted to have an *s*-polarization to *p*-polarization ratio of 50: 50, the LC sample served as a passive HWP and passively changed the linear SOP of the probe beam to 100% *p*-polarization. Under 365-nm UV light exposure (2 min), the LC sample changed the SOP of the probe laser causing it to become 50% *p*-polarized, as shown in Fig. 2a (blue square in the web version), and 40% *s*-polarized, as shown in Fig. 2b (blue square in the web version). Under 532-nm laser exposure (2 min), the LC sample changed the SOP of the probe laser to become 25% *p*-polarized, as shown in Fig. 2a (green circle), and 65% *s*-polarized, as shown in Fig. 2b (green circle). Almost 20% of the linear SOP of a probed laser passing through BMAB-doped BPLC film can be controlled and switched by alternating UV and visible light irradiation. Fig. 2c shows the POM images of the BMAB-doped BPLC film under UV and visible light exposure. Before UV light exposure, the BPLC showed a cholesteric phase of planar texture. Under UV light exposure, the bent-like *cis*-BMAB disturbed the cholesteric phase and changed the phase to be isotropic. Visible light irradiation generated a rod-like *trans*-BMAB and reverted the LC to a cholesteric phase. The phase transition between cholesteric and isotropic was reversible by alternating UV and visible light irradiation.

Fig. 3 shows the linear SOP switching mechanism inside the LC film that involves using two rubbed substrates. Before light exposure, the BPLC was aligned by the parallel oriented substrate and the SOP of the probe beam showed 100% *p*-polarization. Under UV light exposure, the *cis*-BMAB disrupted the BPLC and changed the SOP of the probe beam. Because the BMAB can serve as the photoaligning agent, the visible light (532-nm laser) irradiation, which serves as the driving force of generating *trans*-BMAB, cannot revert the LC orientation to the original alignment. Therefore, the original SOP of 100% *p*-polarization dropped to 25%, as shown in Fig. 2a (green circle). The effect of photoalignment from *trans*-*cis* photoisomerization of BMAB under UV and visible light exposure caused the SOP to become 65% *s*-polarized, as shown in Fig. 2b (green circle). The optically switchable HWP was achieved by the BMAB-doped BPLC under alternating UV and visible light irradiation conditions. A controlled experiment without the use of rubbed substrates showed no reversible switching of SOP in the same BMAB-doped BPLC film, indicating that a stable photoaligned Azo derivative is necessary if rubbed substrates are not used.

We further demonstrated an optically switchable LC HWP without the use of rubbed substrates. The axially symmetric, passive polarization converter was created using photoalignment techniques, as shown in Fig. 1a, using an NLC containing two Azo derivatives, MR and BMAB. Fig. 4 depicts the transmittance (*T*) of the probe beam dependent on the β angle (*T* vs. β), which is the angle between the polarization axis and the LC director [19]. The

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