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Broadband mid-infrared polarization rotator based on optically addressable LCs

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Abstract: This work proposes a mid-infrared polarization rotator that incorporates a twisted nematic liquid crystal (TNLC) cell with a photo-controllable alignment layer. The TNLC device with a sufficient phase retardation can act as an achromic polarization rotation device over a wide wavelengths range and thus can rotate the polarization of a mid-IR laser beam. The photo-alignment technique enables TNLCs with arbitrary twisting angles to be generated by the use of visible polarized addressing light to control the directors of the photo-alignment layer. Therefore, arbitrary rotation angles of the polarization axis of a linearly polarized mid-IR laser beam can be realized. Moreover, the rewritable property and reliability of this polarization rotator are experimentally verified. The flexibility of polarization control for broadband mid-IR opens up a large range of potential mid-IR applications.

OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices; (260.3060) Infrared.

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1. Introduction

Mid-infrared (mid-IR) photonics have been attracting considerable attention for a long time, especially because of their importance in chemical and biomolecular sensing, free space communication, and spectroscopy [1–3]. The mid-IR, which is a spectral region that spans the wavelength range of 3–8 μm, involves with resonance of many strong fundamental vibrational molecular bonds of various molecules, including C-H, C = C, and O-H, making it a relatively attractive target of scientific and technological research [4]. Generation of coherent mid-IR used to be challenging, but can now be realized by advanced quantum cascade lasers, fiber lasers, or compact optical parametric oscillators [5–7]. The development of other mid-IR optical devices such as polarization controllers, phase shifters, absorbers, and mirrors has become urgent. In particular, most optical systems require a polarization controller, which is an optical element for manipulating the polarization state of light. Numerous studies have been conducted to develop mid-IR polarization controllers [8–10]. For example, Khanikaev *et. al*. demonstrated a polarization converter that exploits introducing asymmetric Fano-resonant meta-surfaces [8]. Such a meta-surface is capable of converting linearly polarized light into circularly polarized light with a high transmission of 40%. Cheng *et. al*. developed a mid-IR polarization converter that used L-shaped graphene nanostructures, which can rotate linearly polarized light by 90° in the reflection mode [9]. The polarization conversion can be tuned by controlling the Fermi energy. However, polarization controllers that are based on resonance structures exhibit only narrowband operation, and polarization conversion cannot be tuned after they are fabricated. The development of a tunable polarization converter with broadband operation remains a challenge.

Nematic liquid crystals (NLCs) are widely regarded as suitable for use in tunable electro-optical devices owing to their large refractive index anisotropy and the ease orientation of their LC directors by external forces [11]. Accordingly, many polarization controllers that are based on NLCs that operate in the visible spectrum have been reported [12–14]. Organic NLCs contain many strong molecular vibration bands with CN absorption at 4.45 μm and absorption by CH in the alkyl chain from 3.4 μm to 3.6 μm. This absorption problem of NLCs

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limits their use in mid-IR photonics but can fortunately be addressed by such methods as deuteration, fluorination, or chlorination [15–17]. Another source of absorption of LC devices in the mid-IR spectrum is from indium tin oxide (ITO) electrodes, which are commonly used to drive LC directors [18]. An ITO material strongly absorbs mid-IR light owing to its free-carrier absorption, and thus its transmission in the mid-IR spectrum is low. The transmission of a 20 nm-thick ITO electrode is only 70% at a wavelength of 3 μm and drops to 50% at 5 μm [19].

To solve the absorption problem caused by ITO electrodes in the mid-IR spectrum, other materials such as silicon, germanium, or graphene have been considered as alternatives to ITO in electrodes. In addition to improvement in electrodes, choosing another method for driving LC directors is also a promising solution. Therefore, this work demonstrates an optically addressable mid-IR polarization rotator. The fabrication and analysis of this broadband mid-IR polarization rotator are reported and its switching reliability is investigated.

2. Fabrication of sample and experimental setup

An intra-cavity optical parametric oscillator (HC Photonics) was employed to produce ~40 mW linearly polarized monochromatic mid-IR laser beam at ~3 μm wavelength [20]. The light source is of compact size (85 × 24 × 21.5 mm^3) and low pump threshold (120 mW at 808 nm). It consists of a 808 nm pump diode, a Nd:YVO4 gain medium, a periodically poled lithium niobate (PPLN) chip, and an output coupler. The mid-IR wavelength can be tuned from 2.7 μm to 3.6 μm by controlling the temperature or selecting different channels of the PPLN chip. For mid-IR photonic applications, the aforementioned absorption problem from LC must be addressed first, so the transmittance of the LC material used in this study, 38 μm-thick E7 (from HCCH), in the mid-IR spectrum was measured by Fourier transform infrared spectroscopy (FTIR) (VERTEX 70v FT-IR spectrometers), as presented in Fig. 1(a). The measured transmission spectrum comprises two absorption bands, which originated in the E7 material, whose broad absorption band at near λ = 3.4 μm is associated with C-H bonds in the alkyl chain and whose narrow absorption band at 4.48 μm is associated with C≡N stretching. Therefore, the LC material can be used in a mid-IR laser with a wavelength of 3 μm to demonstrate the device operation, and its transmittance is about 97% at 3 μm wavelength.

In the device configuration of a TNLC cell, the E7 are sandwiched between two sapphire substrates that are transparent to the mid-IR spectrum, and separated by 38 μm-thick Teflon spacers. The sapphire substrates have different surface treatments. The inner surface of the top substrate was coated with a PI layer and rubbed along the x-axis, while that of the bottom substrate was coated with a photo-alignment layer (PAAD-72, Beam Co.). The NLCs were injected into the empty cell in an isotropic state, and then cooled to room temperature. The TNLC cell was thus formed. The LC directors close to the top substrate are uniformly aligned along the x-axis, and those next to the bottom substrate could be uniformly aligned in an arbitrary direction by laser-induced photo-alignment. Figure 1(b) schematically depicts the experimental setup, consisting of two system-, a photo-alignment system and a mid-IR polarization measurement system. In the photo-alignment system, a 405 nm DPSS (Diode-Pump Solid State) laser, whose wavelength was close to the peak absorption wavelength, 424 nm, of the photo-alignment material (PAAD-72), was used as a pumping light source. A quarter wave-plate and a linear polarizer were utilized to control the polarization state of the incident laser light. In the mid-IR polarization measurement system, the mid-IR laser with a wavelength of 3 μm served as a probing light source. The mid-IR laser emitted multi-wavelengths (1064, 1648, and 3001 nm), so a germanium (Ge) filter was used to permit only 3 μm light to pass through the TNLC cell. To realize the waveguide effect of TNLCs, the mid-IR laser had to incident on the TNLC cell from the side of the rubbed PI layer and the input linear polarized light had to be parallel to the rubbed direction of the rubbed PI layer. A mid-IR polarizer and a thermopile photo-detector were used to verify the angle of rotation of the linearly polarized light after it had passed through the TNLC cell.

The operation of the optically switchable polarization rotator is based on the wave-guiding effect of TNLC. For 3 μm mid-IR laser light, a TNLC cell with a relatively large cell gap of 38 μm satisfies the Mauguin condition ($d\Delta n >> \lambda$), where d is the cell gap, Δn is the LC birefringence, andλ is the wavelength [21–23]. Hence, when mid-IR laser light is incident upon the TNLC cell, its polarization axis rotates through the twisted structure of the cell. For a given TNLC cell in which the top LC directors are aligned along the x-axis by the PI-rubbed layer, the twisted structure can be modified by changing the direction of the LC directors in the other substrate, which is coated with photo-alignment material. Exposed to the light from a 405 nm pumping laser, the LC directors on the photoalignment layer-coated substrate are homogeneously aligned perpendicular to the polarization direction of the laser light and remain so aligned after the pumping laser has been switched off [24, 25]. Therefore, an arbitrary angle of rotation from 0° to 90° of the linear polarized mid-IR laser can be achieved.

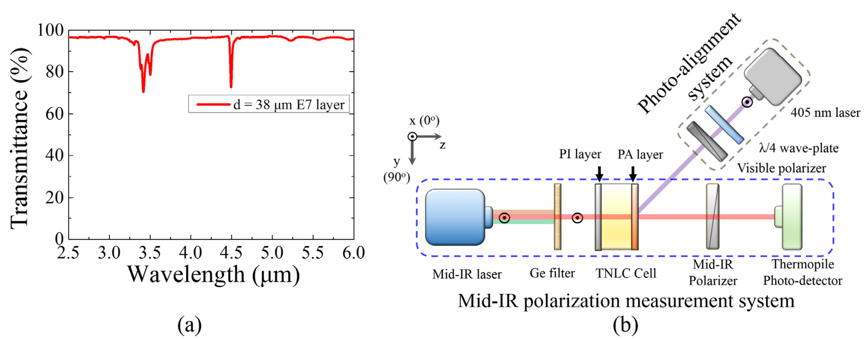

Fig. 1. (a) Transmission spectrum in mid-IR regime, of 38 μm-thick E7 layer; (b) experimental setup for photo-alignment and mid-IR polarization measurement.

3. Results and discussion

To elucidate the optical addressing process of the TNLC cell, variations of the exposure time for the photo-alignment using 405 nm laser light were measured, as shown in Fig. 2. Initially, the LC directors in the TNLC cell were homogeneously aligned (0° TN state) and the transmission axis of the mid-IR polarizer was perpendicular to the polarization state of the mid-IR laser. Accordingly, the mid-IR laser was blocked by the polarizer, and its intensity was zero. When the 0° TN state was optically switched to the 90° state by exposure with 405 nm laser light, the direction of polarization of the mid-IR light was gradually rotated parallel to the transmission axis of mid-IR polarizer and the transmittance increased to maximum. The time for the transmittance to rise from its minimum to its maximum was defined as switching time of the TNLC cell. The relevant measurements indicate that, as the intensity of the 405 nm laser light increased, the switching time reduced. When the intensity of the 405 nm laser was increased from 26 to 194 mW/cm^2, the switching time of the TN cell was reduced from 245 to 34 s. Based on these results, an intensity of 162 mW/cm^2 was chosen in the subsequent experiment (switching time ~31 s).

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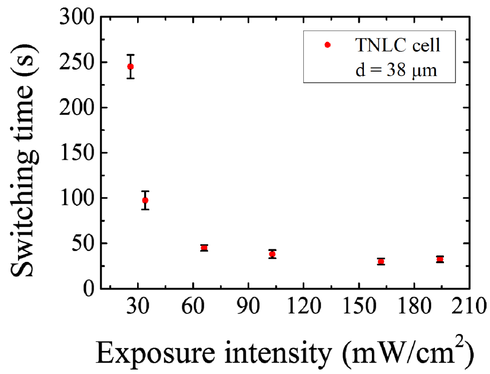

Fig. 2. Dynamic switching time of proposed device with 405 nm laser light.

To verify the photo alignment effect, seven twisted structures with twisting angles of 15°, 30°, 45°, 60°, 75°, and 90° were formed in one TNLC cell using multiple photo-alignment processes, and then observed in visible light. Figure 3(a) presents the images of the TNLC cell between a polarizer and an analyzer. The transmission axis of the polarizer was set to 0°, while that of the analyzer was increased from 90° to 180° in steps of 30°. The unpolarized backlight was linearly polarized by the linear polarizer and its polarization axis was rotated through an angle that depended on the twisting angle of the TNLCs. The output intensity depends on the angle between the polarization axis of the linearly polarized light after it has passed through the twisted structure and the transmission axis of the analyzer (as depicted in Fig. 3(b)). If the polarization axis of the linear polarized light after it has passed through the twisted structure is parallel to the transmission axis of the analyzer, the output is bright. If the output polarization axis of the linearly polarized light is perpendicular to the transmission axis of the analyzer, then the structure is in the dark state because the analyzer blocks the light. Notably, the output color is that of the backlight, indicating the rotation of polarization is achromic and thus associated with extreme broadband operation.

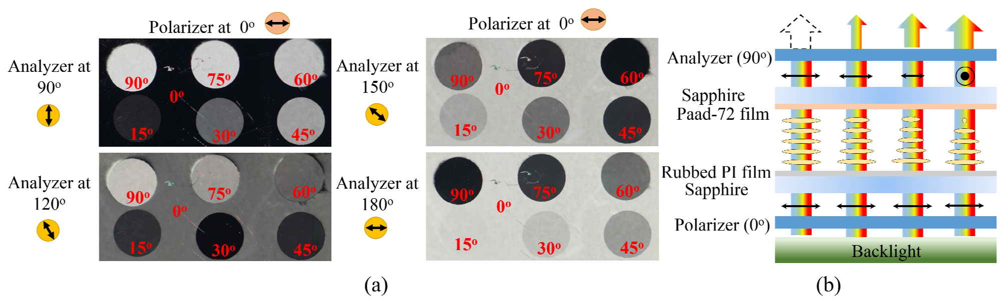

Fig. 3. (a) Images of TNLC cell with various twisted structures between a polarizer (at 0°) and an analyzer (at 90°, 120°, 150°, and 180°), observed on a backlight module, and (b) output brightness of TNLC cell with various twisted structures under crossed polarizers

The rotation of polarization in the mid-IR spectrum is verified. The 0°, 30°, 60°, and 90° TNLC cell is addressed in situ using a linearly polarized 405 nm photo-aligned laser with its polarization axis at 90°, 120°, 150°, and 180°, respectively. Figure 4(a)-4(d) plot polar graphs of the transmittance of the linearly polarized mid-IR laser following the photo addressing. The passing of the linearly polarized mid-IR laser light through the photo addressed TNLC cells rotated its polarization axis from 0° (along x-axis) to 0°, 30°, 60°, and 90° (along y-axis), respectively. The measurements reveal that the output linear polarization axis of the mid-IR laser follows the alignment of the LC directors on the photo-alignment film.

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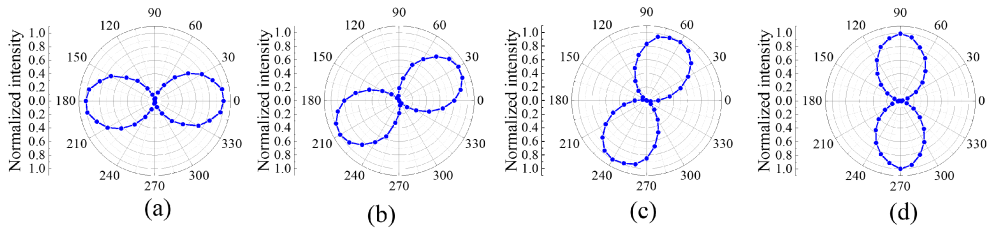

Fig. 4. Polar graphs of transmittance of linearly polarized mid-IR laser light after it has passed through (a) 0°, (b) 30°, (c) 60°, and (d) 90° TNLC cells.

To confirm the reversibility and stability of the TNLC cell, switching processes were repeated and the angles of rotation of the linearly polarized mid-IR laser light were measured each time. Figure 5(a) plots the reversible optical switching between 0° and 90° TNLCs. Clearly, the twisting angle of the TNLCs between 0° and 90° was independent of the number of switching cycles. After 30 optical switchings, the photo-alignment effect continues, and the images of the 90° TNLC cell under the parallel- and crossed-polarized microscope (POM) still exhibit excellent dark and bright states, as shown in Fig. 5(b).

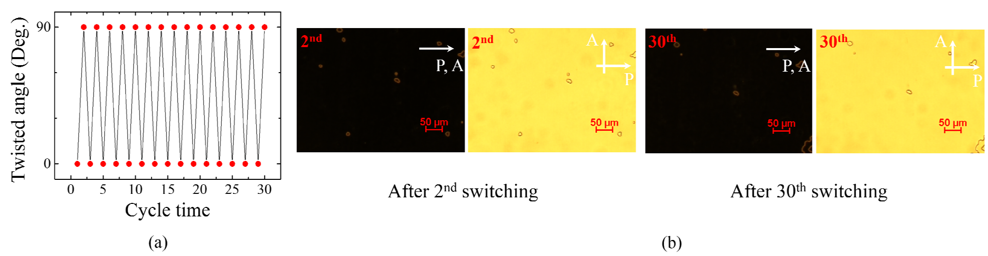

Fig. 5. (a) Dependence of twisting angle of TNLC cell on number of switching cycles, and (b) microscopic images of 90° TNLC cell under crossed and parallel polarizers after second and 30th switching.

A 38 μm-thick cell suffices to cause the TNLC therein to satisfy the Mauguin condition for 3 μm mid-IR spectrum. However, for broadband 3 to 8 μm mid-IR spectrum, a cell that is at least three times as thick is required. To demonstrate the feasibility of the broadband mid-IR polarization rotator, a 250 μm-thick TNLC cell with a photo-controllable alignment layer was fabricated and characterized. The 250 μm-thick E7 layer still has a high transmittance of 92% at 3 μm wavelength, measured by FTIR. Figure 6(a) displays images of the 90° TNLC cell under parallel- and crossed-POM. The 90° TNLC cell with a thickness of 250 μm exhibits high contrast and good alignment quality. Furthermore, the ability of the 250 μm-thick TNLC cell to rotate the direction of polarization of 3 μm mid-IR laser light was investigated. As expected, the polarization direction of linearly polarized mid-IR laser light that passed through the 0° and 90° TNLC cell was rotated 0° and 90° respectively, as presented in Fig. 6(b). Figure 6(c) shows the variations of the exposure time for the photo-alignment of 38 and 250 μm-thick TNLC cell using 405 nm laser light. The experimental results reveal that the switching time of the 38 μm-thick TNLC cell is shorter than that of 250 μm-thick TNLC cell, which is consistent with the behavior of another commonly used photo-alignment material SD1 [26]. The time difference between 38 and 250 μm-thick E7 cell can be gradually reduced as the exposure intensities increases. The switching time of the 250 μm-thick TNLC cell can be reduced to around 1 min with exposure intensity of 194 mW/cm^2. So far, various methods for improving the response time of photo-alignment have been reported. The easiest method is to reduce the cell gap using the Gooch- Tarry first minimum condition or a high birefringence LC. Operation under the Gooch- Tarry first minimum condition can effectively reduce the $d\Delta n$ requirement to 0.866λ. However, it needs a precise control in

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thickness of the TNLCs and only exhibits narrowband operation due to the chromatic dispersion. Besides, the response time of photo-alignment can be effectively improved by selecting LC hosts with a small twist elastic constant (K_{22}) and suitable photo-alignment materials like SD1. Through the optimization of materials, a fast photo-alignment with its response time of 100 ms can be achieved [27]. Although no broadband mid-IR light source was available for testing, based on the Mauguin condition, the proposed polarization rotator with 250 μm-thick TNLCs should have an extremely wide working wavelength range that covers the entire mid-IR spectral region from 3 to 8 μm.

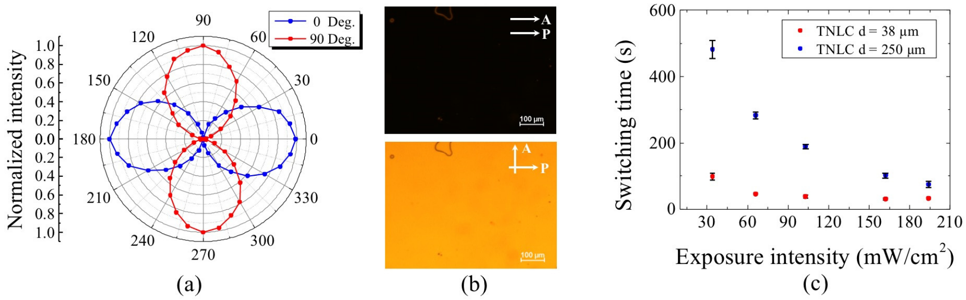

Fig. 6. (a) Polar graph of transmittance of linearly polarized mid-IR laser light through 0° and 90° TNLC cells (250 μm), (b) microscopic images of 90o TNLC cell (250 μm) under crossed and parallel polarizers, and (c) dynamic switching times of the 38 and 250 μm-thick TNLC cells with 405 nm laser light.

4. Conclusion

This work demonstrates a mid-IR polarization rotator that is based on TNLCs with a single-sided photo-alignment layer. The twisted structure of the TNLCs can be switched by irradiation under 405 nm laser light with different polarization directions, and it can rotate the polarization of linearly polarized input mid-IR laser light. Single-sided photo-alignment was used to achieve arbitrary polarization rotation angles between 0° and 90° for mid-IR laser light, and local alignment of LC directors was realized. Such a TNLC-based polarization rotator has many advantages, such as an arbitrary rotation angle, an extremely large bandwidth, and rewritability. It therefore has great potential for use in mid-IR photonics.

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