DYNAMIC, INFRARED BANDPASS FILTERS
PREPARED FROM POLYMER-STABILIZED
CHOLESTERIC LIQUID CRYSTALS (POSTPRINT)

Kyung Min Le
Azimuth Corporation

Shin Mou and Timothy J. White
AFRL/RX

Bradley Worth, II and Vincent P. Tondiglia
University of Dayton

Joshua Myers
Wright State University

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Interim Report

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**6. AUTHOR(S)**  
1) Kyung Min Le - Azimuth Corporation  
2) Shin Mou and Timothy J. White - AFRL/RX  

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**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**  
1) Azimuth Corporation  
4027 Colonel Glenn Hwy 230  
Beavercreek, OH 45431  

2) AFRL/RX  
Wright-Patterson AFB, OH 45433  

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We report on the formulation and electrical control of the position and bandwidth of reflective bandpass filters prepared from cholesteric liquid crystal (CLC) in the infrared (3–5 μm). These filters are prepared from alignment cells employing infrared transparent electrodes and substrates. The optical nature of the electrodes is shown to strongly influence the resulting transmission of the bandpass filters outside of the spectral reflection.  

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<td>Timothy White</td>
<td>(937) 255-9551</td>
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6. AUTHOR(S)
   3) Bradley Worth, II and Vincent P. Tondiglia – University of Dayton

   4) Joshua Myers – Wright State University

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

   3) University of Dayton, 300 College Park Ave,
      Dayton, Ohio 45469

   4) Wright State University, 3640 Colonel Glenn Hwy,
      Beavercreek, OH 45435
Dynamic, infrared bandpass filters prepared from polymer-stabilized cholesteric liquid crystals

BRADLEY WORTH II,1,2 KYUNG MIN LEE,1,3 VINCENT P. TONDIGLIA,1,2 JOSHUA MYERS,1,4 SHIN MOU,1 AND TIMOTHY J. WHITE1,*

1Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Ohio 45433, USA
2University of Dayton, Electro-Optics Program, Dayton, Ohio 45469, USA
3Azimuth Corp., 4027 Colonel Glenn Highway No. 230, Beavercreek, Ohio 45431, USA
4Wright State University, Department of Electrical Engineering, Beavercreek, Ohio 45431, USA
*Corresponding author: Timothy. White.24@us.af.mil

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We report on the formulation and electrical control of the position and bandwidth of reflective bandpass filters prepared from cholesteric liquid crystal (CLC) in the infrared (3–5 μm). These filters are prepared from alignment cells employing infrared transparent electrodes and substrates. The optical nature of the electrodes is shown to strongly influence the resulting transmission of the bandpass filters outside of the spectral reflection. © 2016 Optical Society of America

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1. INTRODUCTION

The cholesteric liquid crystal (CLC) phase self-organizes into a helical structure that results in a periodicity in the refractive index similar to a one-dimensional photonic bandgap [1]. Accordingly, these materials are selectively reflective. At normal incidence, the reflection wavelength and bandwidth are simply products of the refractive index and pitch. The pitch of CLCs is dictated simply by the ratio of the chiral dopant to the nematic host, readily preparing reflective materials spanning the optical regime of electromagnetic spectra.

Subjecting CLC mixtures to external stimuli, such as temperature [2], has been long known to introduce changes to the pitch that result in the color change popularly used in consumer goods, such as aquarium thermometers. As exhaustively detailed in a recent review [3], considerable research has focused on generating dynamic changes in the position or bandwidth of the selective reflection of CLCs when subjected to electrical or optical stimuli. Our group has recently reported on formulations prepared from negative dielectric anisotropic nematic liquid crystal hosts that can be subjected to electrical or optical stimuli. These previous studies have focused on formulations prepared from negative dielectric anisotropic nematic liquid crystal hosts that allow for exceptionally large tuning range or bandwidth control when the CLC mixtures are stabilized with polymers [4–9]. The mechanism detailed in these examinations points to ion-facilitated electromechanical distortion of the polymer stabilizing network [6–8]. By employing different monomers, photo-polymerization conditions, and additives, the network structure can be affected and accordingly allows for a range of electro-optic responses.

Optical filters in the infrared spectrum are comparatively difficult to fabricate because of the required thicknesses [10] and the associated stress of conventional oxide coatings [11–14]. Prior examinations have detailed CLCs both in low molar mass as well as polymeric forms as potential methods to simply and cheaply prepare optical filters in the infrared spectrum [15–21]. Here, we report on an approach to prepare dynamic infrared filters in which the position or bandwidth of the spectra rejection can be shifted by simply applying a fairly low-voltage DC field.

2. RESULTS AND DISCUSSION

Polymer stabilization of cholesteric liquid crystals (PSCLCs) prepared with negative dielectric anisotropy nematic liquid crystal hosts exhibit dynamic responses to applied DC fields. In this work, we demonstrate control of the position or bandwidth of the selective reflection of PSCLCs in the mid-wave infrared (MWIR) region of the electromagnetic spectrum. The basic assembly of an LC alignment cell is illustrated in Fig. 1(a). Typically, alignment cells are prepared with glass, which, as evident in Fig. 1(b), exhibits minimal transmission in the 3–5 μm spectral range. The commonly used transparent electrode indium-tin-oxide (ITO) further decreases the transmission. To prepare a MWIR device, we secured and screened...
Fig. 1. (a) Illustration of a liquid crystal cell prepared from infrared transparent substrates (sapphire), alignment layers (polyimide or Elvamide), infrared transparent electrodes (graphene or silver nanowires), and filled with a cholesteric liquid crystal mixture. (b) Transmission spectra of substrates and transparent electrodes: glass (i), ITO coated glass (ii), sapphire (iii), sapphire coated with graphene (iv), and sapphire coated with AgNW (v). (c) Transmission spectra of an alignment cell prepared from sapphire with AgNW electrodes filled with the nematic liquid crystal mixture ZLI-2079 (i) and a CLC mixture prepared by mixing 1 wt. % R1011 and ZLI-2079 (ii). Polarized optical micrographs of a PSCLC sample at (d) 0 V, (e) 45 V, (f) 160 V, and (g) after field removal (0 V).

We now demonstrate that the electro-optic responses previously reported in the visible and NIR portions of the spectra can also be observed in this spectral region, uniquely enabling the preparation of tunable MWIR filters or mirrors. CLC formulations prepared with the negative dielectric anisotropic nematic liquid crystal ZLI-2079 and the chiral dopant R1011 (1 wt. %) were stabilized with a polymer network prepared by photo-polymerization of 6.5 wt. % of the liquid crystalline diacylate monomer RM82 initiated with 1 wt. % Irgacure 651. The polymer stabilizing network was formed within the samples by photoinitiated polymerization with 200 mW/cm² of 365 nm light (Exfo) for 15 min. As is evident in Figs. 3(a) (AgNW electrodes) and 3(b) (graphene electrodes), the mixture exhibits a selective reflection centered at 2.38 μm. As with the CLC mixtures in Fig. 1(c), in the cell prepared with AgNW performance. However, the ease of preparing and coating AgNW may be desirable in certain implementations.

A second challenge of preparing a MWIR device is achieving high reflectivity while maintaining minimal insertion loss to the overall transmission. Based upon known numerical models of light transmission and reflection in cholesterics, such as the Jones or Berreman methods [22–24], at least 10 pitches are required for a fully reflective notch. At 5.5 μm and assuming an average refractive index of 1.6, the pitch length is approximately 3.4 μm. Thus, to realize a saturated reflection at 5.5 μm requires a minimum cell thickness of 35 μm. At such large thicknesses, the relative anchoring strength of the surface alignment coatings is critical to enforce a strongly anchored alignment through the sample thickness. Figure 2(a) plots transmission spectra taken from alignment cells filled with the same CLC mixture over a range of thicknesses. As expected, cells with 30–36 μm thickness are not largely different from those of 50 μm thickness. However, as evident in Fig. 2(a), the transmission dips for CLC cells with 100 μm thickness. The decrease in transmission across the 2–5 μm range is due to scatter associated with defects that form due to the limited anchoring strength, especially in the central region of the cell gap. For clarity, Fig. 2(b) plots the reflection notch depth and transmission at 2 μm as a function of the cell thickness. For this paper, a cell thickness of 50 μm was chosen. The in baseline transmission increases from Fig. 1 to Fig. 2 due to the lack of graphene or AgNW conductive layers. The peaks evident in the spectra in Fig. 2(a) are due to the IR absorption of the material that becomes evident at these thicknesses.
electrodes, etalon fringes are overlaid onto the optical properties of the material and substrates. Upon the application of a DC field of as much as 110 V, the position of the reflection notch tunes across the MWIR to eventually reach a value of 4.90 μm. Notably, the voltages necessary to drive the change in reflection notch position are slightly different between the two types of electrodes; this could be attributable to slight differences in the PSLC composition, stabilization strength, or other factors. In the 50 μm cells, the reflection notch depth is fairly stable across the 2.5–5.5 μm tuning range. As detailed in a recent examination, due to the electromechanical mechanism that enables the electro-optic responses reported here, only a portion of the pitches red-shift, and thus, preparing these optical elements with 50 μm thicknesses clearly is sufficient to retain a saturated reflection of nearly 50%.

Adjusting the photo-polymerization conditions generates a heterogeneous stabilizing network that results in symmetric and non-uniform displacement of the pitch across the cell gap. In this way, we demonstrate the ability to make a variable reflector (bandpass filter) in the MWIR. The bandpass filter was realized by exposure to the lower UV intensity and shorter exposure time than the red-shifting samples during the photo-polymerization process. The polymer stabilizing network for the bandpass filter was formed by photo-polymerization with about 10 mW/cm² of 365 nm light (Exfo) for 30 s. The formulation examined here was intentionally prepared such that the reflection is hidden within the absorption of ZLI-2079. Thus, the optical element is "transparent" in this state. Figures 4(a) (AgNW electrodes) and 4b (graphene electrodes) plot transmission spectra taken at voltages ranging from 0 to 20 V. As is clearly evident in Figs. 4(a) and 4(b), the reflection notch broadens and extends from the absorption band to cover as much as 2500–4200 nm, a bandwidth of nearly 2000 nm.

Due to the collection speed of the spectrometer employed in this study, we were not able to directly measure the response time of the devices. However, our prior investigations of reflection wavelength tuning and bandwidth broadening have reported on-time responses as low as 1 s and off-time recovery of the original reflection in 1–5 s. The position of the reflection wavelength as a function of the applied voltage is approximately linear in this study, as also reported in our prior investigations [6,8].

3. CONCLUSIONS

In conclusion, dynamic MWIR PSLC filters are demonstrated, in which the position or bandwidth of the reflection can be modulated by the application of an DC field. Large response range, high out-of-band transmittance, and good in-band notch depth demonstrate the PSLCs as a MWIR filter.

Clearly, the large absorption embedded in these devices is not ideal. Towards this end, future research would benefit from nematic liquid crystals with negative dielectric anisotropy optimized for utility in the infrared region. A number of recent investigations [25–27] have reported on the formulation of IR transparent nematic liquid crystals that propose and realize a number of methods to accomplish this with positive dielectric anisotropy materials.

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REFERENCES