Tunable Narrow-bandpass Filter Using Blue Phase Liquid Crystal Etalon for Real-time Multi-spectral Imaging Systems

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ABSTRACT

We proposed a tunable narrow-bandpass filter using a blue phase liquid crystal etalon filter and a multi-bandpass interference filter for real-time multi-spectral imaging systems. We theoretically clarified this filter has high transmittance > 80% and confirmed a control of transmission wavelengths can be achieved by this filter.

1 INTRODUCTION

Spectral imaging systems are attracting attention as a means for non-destructive analysis via measurement of optical characteristics. These systems also acquire wavelength information that cannot be obtained from color images. By processing wavelength information, spectral imaging systems can determine the composition and structure of objects. These systems have been studied for medical, agricultural, industrial and other applications. Recently, Small-sized spectral imaging systems are anticipated for real-time remote sensing and dynamic analysis. Conventional methods, such as wavelength scanning, spatial scanning, and time scanning [1], have difficulty in achieving high-speed responses and downsizing.

To solve these problems, we reported a liquid crystal (LC) filter consisting of a multi-bandpass interference filter and three LC devices [2]. This filter can control transmission wavelengths by the interference filter transmitting only plural wavelengths and the three LC devices blocking non-transmitted wavelengths. This filter achieved spectroscopy to be performed at 22.7 fps. However, improvements are still required in the LC devices used in the filter. As the LC devices used retardation of nematic LCs, transmittance was decreased due to the polarizing plates and the response time increased in the case of off-switching.

In this paper, we propose a high-speed, high-transmittance, electrically tunable filter for real-time spectral imaging systems using blue phase LC (BPLC) etalon.

2 STRUCTURAL DESIGN OF THE HIGH TRANSMITTANCE AND HIGH-SPEED FILTER

Figure 1 shows the structure of the proposed electrically tunable narrow-bandpass filter. The device consists of a multi-bandpass interference filter and a polymer-stabilized BPLC (PSBPLC) etalon filter. The interference filter has plural narrow-band transmission wavelengths and we designed the transmission wavelength to be 960 and 1,050 nm. The PSBPLC etalon filter has many narrow-band transmission wavelengths because of interference between reflective electrodes. This device controls transmission wavelengths by matching them between the two filters. Equation (1) shows the transmission wavelengths (defined as λ) of the PSBPLC etalon filter.

$$\lambda = \frac{2nd}{m - P/\pi} \qquad (1)$$

Here, n is the refractive index of PSBPLCs in the polarization direction, d is the thickness of the PSBPLC layer, m is an integer, and P is the phase change caused by one reflection. Since PSBPLCs can perform polarization-independent refractive index modulation at high-speed through application of a voltage [3], the PSBPLC etalon filter can control transmission wavelengths with high transmittance at high-speed. Therefore, by selecting transmission wavelengths with this device, real-time multi-spectral imaging can be performed with high sensitivity.

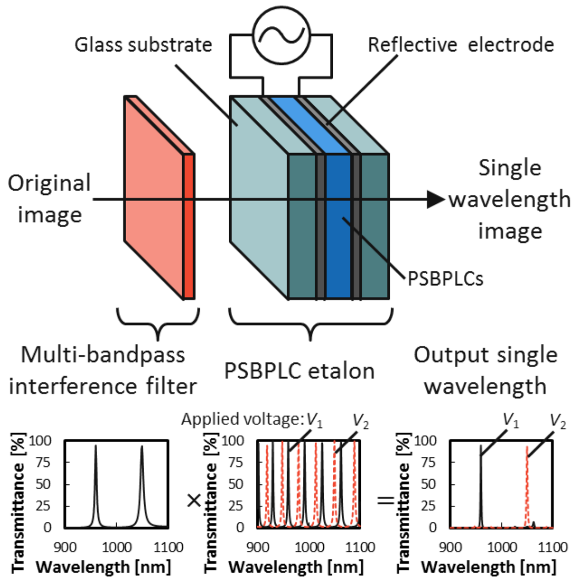

Fig. 1 Structure and transmittance of the electrically tunable filter using the PSBPLC etalon filter.

In the proposed device, the necessary characteristics of the PSBPLC etalon filter include the ability to control the transmission spectrum, wide wavelength bands with low transmittance between transmission wavelengths ("cutoff" wavelength bands) that block unnecessary wavelengths, and high transmittance of necessary wavelengths. To satisfy these three conditions, we simulated the transmission spectrum of the PSBPLC etalon filter and evaluated it in a fabricated cell.

3 RESULTS AND DISCUSSION

3.1 Spectral simulation

Table 1 shows the composition of the PSBPLC etalon filter used in the simulation. Silver (Ag) thin film (thickness: 15 nm) was used as the reflective electrode because it satisfied the conditions of wide cutoff wavelength bands and high transmittance according to the calculation results. In addition, as the simulation was performed in a narrow near-infrared wavelength band (900–1,100 nm), we ignored the wavelength dispersion of *n* of PSBPLCs. We calculated transmission spectrum changes by refractive index modulation of PSBPLCs and designed the refractive index so that the transmission wavelength is 960 and 1,050 nm.

Table 1 Composition of the PSBPLC etalon filter used in the spectral simulation

layer	refractive index	thickness
Glass Substrate	1.5	2.8 mm
Reflective electrode	Ag	15 nm
PSBPLCs	1.45-1.5	10 µm

Figure 2 shows the simulated transmission spectrum changes of the PSBPLC etalon filter with refractive index modulation. At wavelengths of 960 and 1,050 nm, the transmittance of the transmission wavelength was > 80%, and the transmittance of the blocked wavelength was < 2%. The results showed that a refractive index modulation of ~0.02 necessary for control of the transmission wavelength between 960 and 1,050 nm, with high transmittance.

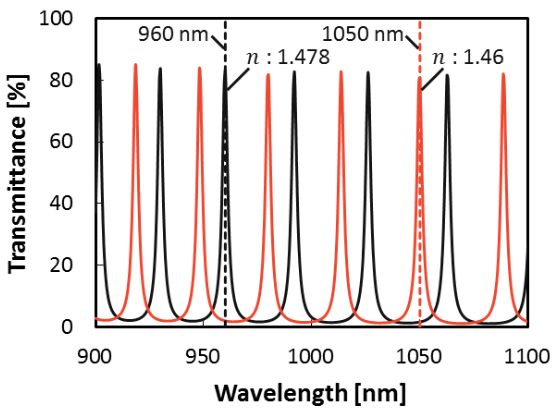

Fig. 2 Simulated transmission spectrum changes of the PSBPLC etalon filter caused by refractive index modulation

3.2 Cell fabrication and measurement of refractive index of PSBPLCs

We fabricated an LC cell and measured the refractive index modulation of PSBPLCs to compare it with the requirements mentioned above. We prepared Ag alloy coated glass substrates (GEOMATEC Co., Ltd.) and LC mixture JC-BP02 (JNC Corp.) composed of LCs, chiral agents, and ultraviolet (UV)-curable monomers. We used Ag alloy because it showed less deterioration than Ag. We fabricated an empty cell with a ~10 µm gap sustained by glass bead spacers and ultraviolet curing resin, 3017 (Three Bond Co., Ltd.). JC-BP02 was injected into the cell via capillary action. Next, the cell was cooled from 53°C to 44°C at 0.1 K/min. Finally, the cell was irradiated with UV light to polymerize the monomers under a UV light intensity of 25 mW/cm^2 with a center wavelength of 365 nm and exposure time of 60 s, and JC-BP02 was turned into PSBPLCs.

Figure 3 shows the measured refractive index modulation (wavelength: 1,000 nm) of PSBPLCs, according to the extended Kerr effect [4]. With application of a voltage of 80 V, the refractive index decreased by about 0.03, from 1.498 to 1.466. This modulation met the requirements obtained by the simulation.

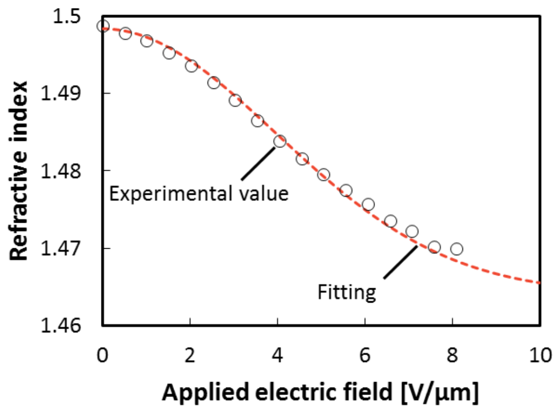

Fig. 3 Measured refractive index modulation (wavelength: 1,000 nm) of PSBPLCs by the extended Kerr effect. The direction of the measured refractive index is a normal direction of the electric field. The electric field is a square wave (frequency: 1 kHz).

3.3 Spectral measurement

We fabricated an LC cell and measured transmission spectrum changes by using a spectrophotometer, V-770 (JASCO Corp.). The cell gap was 9.89 µm. Figure 4 shows transmission spectrum changes by applying voltage (20 V and 60 V). At each voltage, the transmittance of transmission wavelengths was > 25%, and the transmittance of the blocked wavelengths was < 5%. As a result, we confirmed that PSBPLCs made it possible to control transmittance wavelengths. However, due to the use of Ag alloy whose lower transmittance and reflectance than Ag, the transmittance of transmission wavelengths was lower than the simulation and the transmittance of blocked wavelengths was higher than the simulation.

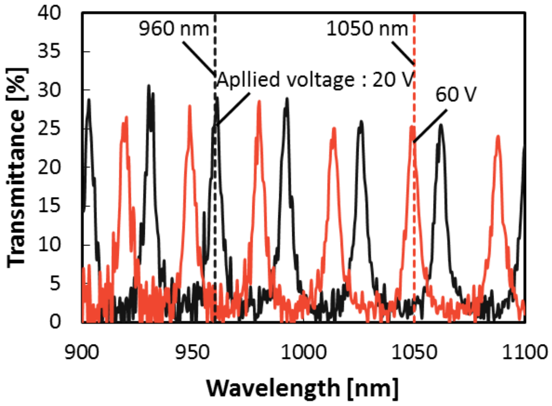

Fig. 4 Measured transmission spectrum changes of the fabricated PSBPLC etalon filter according to the applied voltage.

4 CONCLUSIONS

In this study, we proposed a high-speed, high-transmittance, electrically tunable filter, based on a multi-bandpass interference filter and a PSBPLC etalon filter, for real-time multi-spectral imaging systems. Spectral simulation demonstrated that it was possible to control transmission wavelengths to 960 and 1,050 nm with high transmittance > 80%. In addition, the measurement results showed that the transmission wavelength could be controlled as well as in the simulation. In future, we will increase the transmittance by optimizing the fabrication conditions of reflective electrodes, and control the transmission wavelengths in two dimensions by improving the cell gap uniformity.

ACKNOWLEDGMENT

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