High-speed Tunable Multi-Bandpass Filter for Real-time Spectral Imaging using Blue Phase Liquid Crystal Etalon

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Abstract We developed a high-speed, electrically tunable multi-bandpass filter using a polymer-stabilized blue-phase liquid crystal etalon and a narrowband multi-bandpass interference filter, for use in real-time multi-spectral imaging systems. We show theoretically that the filter exhibits high-level transmittance ($\geq 80\%$) by using an Ag film as the reflective film used in the etalon. We confirmed that the filter allows for high-speed switching of the transmitted wavelength; the response time is about 1 ms. The filter enables high-transmittance, high-speed spectroscopy. Therefore, high-sensitivity real-time multi-spectral imaging at a frame rate of 60 fps or more can be expected in the future.

Keywords: multi-spectral imaging, liquid crystal tunable filter, blue phase liquid crystal, fabry-pérot etalon, fast switching, high-transmittance.

1. Introduction

Spectral imaging systems acquire object wavelength information by combining spectroscopy and imaging¹⁾. After processing this information, the object configuration and structure can be determined by reference to its transmission, reflection, and absorption characteristics. Thus, the systems find applications in agriculture, medicine, industry, forestry, and fisheries²⁾⁻⁶⁾. Recently, real-time sensing has been expected for applications such as blood glucose measurement and remote sensing with small spectral imaging systems. However, conventional spectroscopic methods such as spatial, space, and time scan systems⁷⁻¹¹⁾ have a problem that it is difficult to realize all of the high-speed, small-size, and high-definition at the same time. In order to solve the problem, a method using a filter using liquid crystal (LC) has been studied. With this method, the light from an object can be obtained without degradation of spatial resolution, thus enabling a high-definition spectral imaging.

Figure 1 shows the structure of LC tunable filter (LCTF)^{7) 8)}. This filter consists of several layers of the LC cell in which a nematic LC and a phase retardation plate

Fig. 1 Structure of conventional LCTF.

are sandwiched between polarizing plates. The optical axes of LCs and phase retardation plates are 45° to the polarizer axis. Transmission wavelengths of LC cell depends on the phase retardation of the LCs and the phase retardation plates. Since the phase retardation is wavelength dependent, the LC cells has multiple transmission wavelengths. Therefore, by overlaying several LC cells and matching the transmission wavelength, only one wavelength can be transmitted. As the phase retardation of LC can be changed by electrically controlling the LC alignment, the transmission wavelength can be switched. Therefore, high-definition spectral images can be obtained by stacking the LCTF and an image sensor. However, some problems must be addressed. First, LC cells exhibit

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Fig. 2 Structure and principle of multi-bandpass LCTF using multi-bandpass interference filter. By multiplying the transmission spectrum of multi-bandpass interference filter and LC filter, single transmission wavelength is obtained as shown in the graphs in the lower figure.

multiple transmission wavelengths with wide full-width-at-half-maximum (FWHM) values; many cells are required to obtain a narrowband single transmission wavelength. This results in a thick filter. Second, sufficient change in phase retardation by the LC layer is required to change the transmission wavelength. Thus, the LC layer becomes thicker, and the response becomes slower due to the elasticity of the nematic LC.

To solve these problems, we previously reported a tunable multi-bandpass filter combined with a narrowband multi-bandpass interference filter and LC cells^{12) 13)} (Fig. 2). In this LC filter, narrowband transmission wavelength is obtained by the interference filter, and the LC layer is designed to block the wavelength other than transmission wavelength as shown in the graphs in the Fig. 2. As a result, a number of LC cell and a thickness of LC layer can be reduced. The transmission wavelength of this LC filter can be changed by applying a voltage to LC layer and switch the blocking wavelength. However, the response is not fast enough to realize high-speed spectroscopy because of the elasticity of the nematic LC. Also, the use of multiple polarizers reduces the transmittance to 25% or less, which makes imaging low-sensitivity. Thus, it is essential to switch transmission wavelengths without using polarizers. In this paper, we developed the LCTF allowing high-transmittance and high-speed switching of transmission wavelengths by using a blue-phase LC etalon.

2. Proposal for high-speed LCTF using blue phase liquid crystal etalon

Fabry-Pérot etalon with an LC (LC etalon)¹⁴⁾ is a filter that does not exploit the phase retardation of LC, it is possible to switch transmission wavelengths without using polarizer. We developed an LC etalon using a polymer-stabilized blue-phase LC¹⁵⁾ (PSBPLC etalon) and proposed a high-speed LCTF¹⁶⁾ by combining a narrowband multi-bandpass interference filter with this LC etalon for high-sensitivity real-time multi-spectral imaging. Figure 3 shows a structure and a principle of our LCTF using PSBPLC etalon. We used the narrowband multi-bandpass interference filter transmitting 960 and 1050 nm considering wavelengths used for near-infrared (NIR) spectroscopic measurement of glucose concentrations in aqueous solution. The FWHM of transmission spectral range was 10 nm and a transmittance was 90%. We obtain a single transmission wavelength by matching the transmission wavelengths of two filters and the transmission wavelength of LCTF can be changed by applying a voltage to the PSBPLC etalon.

In the LC etalon, the LC layer is sandwiched between two reflective films. Incident light triggers interference between the films; only the resonant wavelength is transmitted. This wavelength is switched by modulating the refractive index of the PSBPLC. A BPLC is an LC

Fig. 3 Structure and principle of high-transmittance and high-speed LCTF using blue phase liquid crystal etalon. By multiplying the transmission spectrum of multi-bandpass interference filter and PSBPLC etalon, single transmission wavelength is obtained as shown in the graph in the lower figure.

with a three-dimensional lattice structure that becomes markedly twisted on the addition of a chiral agent and the refractive index of which is identical to that of the isotropic phase when no voltage is applied. A voltage uniformly modulates the refractive index in the direction perpendicular to the electric field. The fast response speed is obtained due to the reorientation in microdomains and the strong polymer network. Thus, the PSBPLC etalon allows for high-speed and polarization-independent switching of the transmission wavelength¹⁷⁾. Compact, high-speed and high-definition spectral imaging is realized by combining the PSBPLC etalon with a narrowband multi-bandpass filter.

To date, there have been reports on the advantages of the PSBPLC etalon, but no reports on the tunable multi-bandpass filter using the PSBPLC etalon. Here, we first investigate the characteristics that the etalon must exhibit to transmit a single wavelength with high-transmittance. Next, we explore refractive index modulation of the PSBPLC required to switch the transmission wavelength. Finally, we fabricate the LC cell and examine a response speed of PSBPLC etalon.

3. Calculation of transmittance characteristics of the PSBPLC etalon

The tunable multi-bandpass filter was designed to transmit the light at two wavelengths, 960 and 1,050 nm considering an application to the NIR spectroscopic measurement of glucose concentrations in aqueous solution. To ensure the transmission of only one of the two possible wavelengths of the tunable multi-bandpass filter, the PSBPLC etalon need to transmit one wavelength with high-transmittance and block the other wavelength. Figure 4 shows the required characteristics of the PSBPLC etalon. First, the peak transmittance of the PSBPLC etalon must be high at the transmission wavelength. The peak transmittance is given by the following equation:

$$T_{\max} = \frac{(1 - A)^2}{(1 - R)^2} \quad (1)$$

where A and R are the absorbance and reflectance of the reflective film, respectively. This equation shows that the peak exhibiting high-transmittance can be obtained by using a reflective film with a low-absorbance and high-reflectance.

Second, to block the other wavelength, the light should be in spectral range with low-transmittance (blocked spectral range) between peaks. For that reason,

Fig. 4 Definition of required characteristics for the PSBPLC etalon to transmit only one of the two possible wavelengths of the tunable multi-bandpass filter.

blocked spectral range needs to be wide. Therefore, we investigated the conditions for a wider blocked spectral range. Since the ratio of blocked spectral range ($\Delta\lambda_{BSR}$) to the spectral range between peaks (free spectral range, $\Delta\lambda_{FSR}$) can be treated as the probability that the wavelength to be blocked is in blocked spectral range, we evaluated $\Delta\lambda_{BSR}/\Delta\lambda_{FSR}$ as a parameter of the width of blocked spectral range.

Here, transmittance of the PSBPLC etalon is given by the following equation:

$$T = \frac{(1 - A)^2}{(1 - R)^2 + 4R\sin^2\left(\frac{\delta}{2}\right)} \quad (2)$$

$$\delta = 2\pi \frac{2nd}{\lambda} + 2P$$

where δ is phase difference between the light that passes through the PSBPLC etalon after one round trip and the light that passes straight through it, n and d are the refractive index and the thickness of PSBPLC, respectively. λ is the wavelength and P is the phase change associated with a single reflection at the reflective film. In this equation, the PSBPLC is considered to be a uniform medium with no spatial variation. According to equation (2), $\Delta\lambda_{BSR}/\Delta\lambda_{FSR}$ can be approximated by the ratio of the difference in δ as in equation (3), under the condition that the PSBPLC is sufficiently thick and the reciprocating optical path length of the PSBPLC etalon ($2nd$) is sufficiently large respect to the wavelength (900-1,100 nm).

$$\frac{\Delta\lambda_{BSR}}{\Delta\lambda_{FSR}} \simeq \frac{\Delta\delta_{BSR}}{\Delta\delta_{FSR}} \quad (3)$$

$\Delta\delta_{BSR}$ is the difference in δ calculated from equation (2) at both ends of blocked spectral range and $\Delta\delta_{FSR}$ is the

difference in δ calculated from equation (2) at both ends of free spectral range. So, instead of $\Delta\lambda_{BSR}/\Delta\lambda_{FSR}$, we use $\Delta\delta_{BSR}/\Delta\delta_{FSR}$ to evaluate the width of blocked spectral range. By transforming $\Delta\delta_{BSR}/\Delta\delta_{FSR}$ using equations (1) and (2), $\Delta\lambda_{BSR}/\Delta\lambda_{FSR}$ is given by the following approximation.

$$\frac{\Delta\delta_{BSR}}{\Delta\delta_{FSR}} = 1 - \frac{2}{\pi} \arcsin \sqrt{\frac{\left(1 - \frac{0.05}{T_{\max}}\right)(1-R)^2}{4R \frac{0.05}{T_{\max}}}} \quad (4)$$

In this equation, we defined spectral ranges where the transmittance is 5% or less as blocked spectral ranges. This equation shows that a wide blocked spectral range can be obtained by using a reflective film with a high-reflectance.

Here, to apply a voltage to the PSBPLC, the reflective film must have the high conductivity. On the basis of the above conditions for the reflective film, we used Ag film as the reflective film¹⁸⁾, and optimized the absorptance and reflectance by adjusting the thickness of Ag film. We calculated the change of the peak transmittance and blocked spectral range with respect to Ag film thickness. We assumed that the PSBPLC and etalon glass have no wavelength dispersion of refractive index and the value is 1.5, and ignored a reflection at the boundary between the glass and the etalon exterior.

Figure 5 shows the change of the peak transmittance and blocked spectral range with respect to Ag film thickness. We derived the results by calculating the reflectance and absorbance from the complex refractive index and thickness of the Ag film by using equations (1) and (4). We found that the peak transmittance of more than 80% was obtained at the film thickness of 15 nm, when the ratio of blocked spectral range was considered to be more than 50% so that more than half of spectral range would be blocked. Therefore, we found that by optimizing the Ag film thickness, only one wavelength can be transmitted with high-transmittance of 80% or more, and the other wavelength is blocked with a probability of 50% or more.

Next, to select and transmit the transmission wavelength, we need to alternately switch between the peak wavelength and blocked spectral range by using the change of transmission spectrum of the LC etalon. Therefore, we investigated the switching of the transmission wavelength by the refractive index modulation of the PSBPLC. Peak wavelengths of the etalon are given by the following equation:

Fig. 5 Calculation result of change of blocked spectral range and peak transmittance of etalon with thickness of Ag film.

$$\lambda_{peak} = \frac{2nd}{m - P/\pi} \quad (5)$$

where m is an arbitrary natural number. Excluding the negligible small effect of P varying with n , the equation shows that peak wavelengths are proportional to the refractive index of the PSBPLC. Similarly, wavelengths of blocked spectral range are proportional to the refractive index of PSBPLC. To shift peak wavelengths and wavelengths of blocked spectral range and switch the transmission wavelength, a large refractive index modulation of the PSBPLC is required. Therefore, we explored how much refractive index modulation is required to switch the transmission wavelength between 960 and 1,050 nm. The thicker the LC layer of the etalon, the easier to switch the transmission wavelength because free spectral range becomes narrower. However, too narrow free spectral range makes blocked spectral range narrow and to block the light becomes difficult. So we investigated switching of transmission wavelength by refractive index modulation with the thickness of the LC layer being 10 μm . This satisfies the condition of the approximation in equation (3). We assumed that the refractive index does not exhibit wavelength dispersion in the range 900-1,100 nm. We used a 15-nm-thick Ag film as a reflective film. The other conditions were the same as those used above.

Figure 6 shows the change in transmission wavelength in relation to the refractive index of the PSBPLC. We derived the results by using equation (2). We found that a refractive index modulation of 0.02 (from 1.478 to 1.460) is necessary to switch transmission wavelength from 960 nm to 1,050 nm. In the next section, we examined that our PSBPLC material meets these conditions, and evaluated the switching of transmission wavelength from experimental results.

Fig. 6 Calculation result of switching transmission wavelength of the etalon by refractive index modulation of the PSBPLC.

4. Design and evaluation of the PSBPLC etalon

First, we examined whether our PSBPLC delivered the refractive index modulation necessary to switch the transmission wavelength. We measured peak wavelengths when a voltage was applied to the LC cell, and derived the refractive index modulation based on the change in peak wavelengths by using equation (5). We prepared Ag alloy coated glass substrates (GEOMATEC Co., Ltd.) with high oxidation resistance instead of an Ag film to prevent changes in optical properties due to oxidation.

To fabricate the PSBPLC, we used the LC mixture (JC-BP02, JNC Corp.), which contains chiral agents, and ultraviolet (UV)-curable monomers. We first fabricated an empty cell with a 10 μm gap sustained by bead spacers and a sealing resin (3035B, Three Bond Co. Ltd.). Next, JC-BP02 was injected into the cell via capillary action at a temperature of 55°C, and the cell was then cooled at 0.1 K/min to 44°C. Finally, the cell was irradiated with UV light (center wavelength, 365 nm) at 19.6 mW/cm² for 60 s to polymerize the monomers. Figure 7 shows a microscope image of the LC cell under the crossed-Nicols polarizer. We confirmed that a BPLC appeared at room temperature. We also observed platelets in the fabricated LC cell. However, there was no light scattering by the platelets, so we considered the effect on the device to be very small.

Figure 8 shows the measurement results of the refractive index modulation of PSBPLC at wavelength of 1,000 nm. The broken line is the approximation derived using the extended Kerr effect¹⁹⁾. At an LC layer thickness of 10 μm , the refractive index changed by about 0.03 (from 1.498 to 1.466) on application of 80 V. From these results,

Fig. 7 Polarization micrograph of the PSBPLC at 25°C with no voltage applied.

Fig. 8 Measurement result of refractive index modulation of JC-BP02.

Fig. 9 Measurement result of transmission wavelength switching of PSBPLC etalon by applying voltage.

we confirmed that our PSBPLC cell meets the condition to switch transmission wavelength.

Next, we evaluated a transmission wavelength switching by using a spectrophotometer (V-770; JASCO Corp.). Figure 9 shows the change of the transmission spectrum when the voltage is switched. The peak wavelength and blocked spectral range within which the transmittance was less than 2%, switched between

Fig. 10 Comparison of calculated transmission spectra of PSBPLC etalon used Ag or Ag alloy thin film.

wavelengths of 960 and 1,050 nm when the voltage changed. Therefore, we confirmed that the PSBPLC etalon sufficiently satisfies the conditions necessary for switching the transmission wavelength. However, the peak transmittance was much lower than calculation results shown in Fig. 6. To clarify the difference of transmittance between theoretical and measured values, we measured the optical properties of the Ag alloy thin film by using a spectroscopic ellipsometer, and found that complex refractive index differed significantly from the theoretical values.

Figure 10 compares the calculated etalon transmission spectrum between the theoretical Ag thin film values and the values calculated when the real optical characteristics of the Ag alloy thin film. The surface reflection of glass are included in this calculation. When the Ag alloy thin film was used, the peak transmittance fell from 84% to 24% and tended to decrease further at longer wavelengths, close to the peak transmittance in Fig. 9. The reason for this is thought to be that the absorbance of the Ag alloy thin film is greater than that of the theoretical Ag thin film, and the absorbance is even greater on the long-wavelength side. Although the optical characteristics of the Ag alloy are different from those of theoretical Ag, the calculated transmission spectrum are almost in agreement with the experimental transmission spectrum in Fig. 9. Thus, the peak transmittance can be improved by using a reflective film with a complex refractive index closer to the theoretical value of Ag.

Finally, we measured the transmission spectrum response time of the PSBPLC etalon. Figure 11 shows the transmittance and voltage waveforms used in the experiment. We used overdrive method²⁰⁾²¹⁾ to accelerate the response speed by using a waveform into which a

Fig. 11 The waveform of transmittance and voltage in overdrive method.

Fig. 12 Optical system for response time measurement.

higher than necessary voltage change is momentarily inserted. The voltage was varied at approximately 8.3 ms intervals, assuming a frame rate of 60 fps. A DC voltage of ± 13 V was applied when the transmission wavelength was 963 nm and ± 52 V when the transmission wavelength was 1050 nm. In addition, as overdrive method, a voltage of 100 V was applied for 0.2 ms when the voltage was increased, and a voltage of 0 V was applied for 1.6 ms when the voltage was decreased. Figure 12 shows the optical system used for measurements. We measured changes in transmittance by using photodetector (CV-RS110; CremoVision Co., Ltd.).

Figure 13 shows the response properties at 963 and 1,050 nm. When contemporaneous responses were compared, the fall time was shorter than the rise time. Therefore, we defined the response time as that between the moment of voltage change and the moment at which the normalized transmittance attained 90%. The switching time from 963 to 1,050 nm was 0.2 ms, the drive time from 1,050 to 963 nm was 1.1 ms, and the response time per cycle was 1.3 ms. Compared to the

Fig. 13 Measurement results of PSBPLC etalon response time.

total response time by using the previously proposed filter shown in Fig. 2 (31.92 ms), the response time was reduced by over 90%. This will enable real-time spectral imaging at a frame rate of 60 fps or more.

5. Conclusion

We proposed a high-transmittance and high-speed electrically tunable multi-bandpass filter by using a PSBPLC etalon and a multi-bandpass interference filter for application to high-sensitivity real-time spectral imaging. Calculation results showed that when an Ag thin film of appropriate thickness is used in the etalon as a reflective film, a high transmittance over 80% is possible, and that the transmission wavelength can be switched via a refractive index modulation of the PSBPLC. We experimentally verified the calculation results, and confirmed the transmission wavelength switching time is as low as 1.3 ms. In the future, we will fabricate an etalon with higher-level transmittance by optimizing the reflective film.

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