Two-Dimensional Spectrum Control of Tunable Filter of Liquid Crystal

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ABSTRACT

The possibility as a tunable filter of liquid crystal capable of two-dimensional spectroscopy is clarified. By stacking liquid crystal layers with different dispersion property of birefringence, the arbitrarily controlling the center wavelength λ_0 and half-value width $\Delta\lambda$ of a single spectrum is realized.

1 Introduction

Half a century has passed since G. H. Heilmeier proposed the application of liquid crystal to display in 1967, and the liquid crystal has progressed remarkably.

It is expected that the importance of liquid crystal with low voltage, low power, thinness and high optical effect will increase in the future. So it is desired to establish a more precise control technique. On the other hand, since it is an organic substance, thousands of types of the liquid crystal has been synthesized, and many properties can be produced by combining them. This research is an attempt to clarify new features of the liquid crystal.

In 1933, B. Lyot stacked multiple birefringence materials and adjusted the retardation Δnd, which is the product of the birefringence Δn of the liquid crystal and the layer thickness d. It was shown that the center wavelength spectrum appears sharply because the transmission on both sides of peak change without changing the center wavelength λ_0[1]. Ishinabe et al. took the lead in narrowing the band in a tunable filter of liquid crystal (TFLC). [2] After that, Terashima et al. proposed a method in which a plurality of narrow spectra of four wavelengths are created by stacking an interference filter and a narrow spectrum can be obtained with a slightly wide half-value width by a birefringence liquid crystal. [3] In narrowing the band, it has been basic to stack layers of the same liquid crystal with different layer thicknesses by half an integral number and apply the same voltage.

The voltage dependence of the birefringence property of liquid crystal has already been studied as a polarization control type display. Based on this knowledge, the center wavelength λ_0 and the half-value width Δλ can be controlled more widely by applying new concept. In this research, the unique point is that we try to realize center wavelength and half-value width control in a wide range by fusing multiple liquid crystals layers, and aim for the TFLC layer with higher controllability.

2 New Concept of Controlling the Spectrum

In the electrically controlled birefringence (ECB) of the liquid crystal layer, assuming that the birefringence Δn, the thickness d, and the wavelength λ of the liquid crystal, the transmittance Tr is given by the following equation (1).

$$Tr = \cos^2(\pi \frac{\Delta nd}{\lambda}) \cdots (1)$$

Here, Δnd/λ represents the number of light waves included in the optical path difference Δnd. As shown in Eq. (1), the number of waves is a quantity that is uniquely linked to the transmittance Tr, and is 100% for integer values and 0% for half-integer values. In this research, the following points will be clarified in order to establish a method for practical application of TFLC, to show the electro-optical effect to improve its function, and to expand the variety of applications.

(1) Clarify the design concept of TFLC and choose from a variety of LCDs
(2) Establish controllability in a wider wavelength range from narrowband to wideband.

In order to realize above aims, it is necessary to satisfy the following two conditions.

Condition (1): Set the main wavelength λ_0 indicating the peak value and fix it avoiding shift.
Condition (2): Change the wavelength dispersion property of the birefringence.

Therefore, in order to satisfy the condition (1), the number of waves $\Delta n_0 d / \lambda_0$ at the main wavelength λ_0 must be constant as an integer. Δn_0 is the value of birefringence at λ_0. On the other hand, under the condition (2), Δnd/λ, which is the number of light waves included in the retardation Δnd, must be changed with respect to the wavelength λ. In the case of a single-layer liquid crystal, the main wavelength λ_0 is determined and

Δn_0 is adjusted by the applied voltage. As a result, Δn at other wavelengths is uniquely determined, so that the variability of the dispersion property is restricted and the condition (2) cannot be satisfied. In solve to this limitation, we propose a birefringence control method in which two types of liquid crystal a and b are stacked. One is a type in which the optical axes of the two liquid crystal layers shown in Figure 1 are parallel and the birefringence is added, and the other is a type in which the optical axes shown in Figure 2 are orthogonal to each other and the birefringence is subtracted.

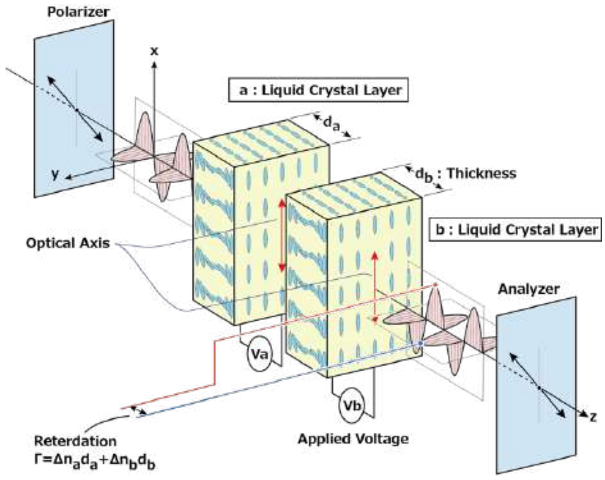

Figure 1 Structure of stacking birefringence layers (addition type) .

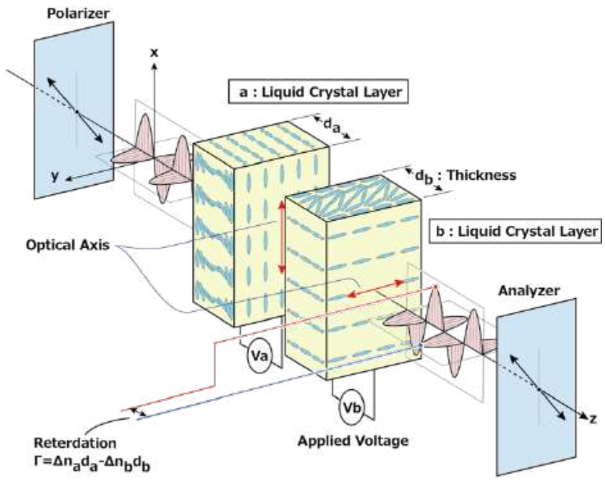

Figure 2 Structure of stacking birefringence layers (subtraction type) .

Figure 3 shows the wavelength dependence of the additive type. λ_0 is the main wavelength set to the maximum transmission, and it is assumed that Δn at λ_0 of the two liquid crystals are the same in this figure. It is adjusted to be constant in order to satisfy the condition (1). After setting this part to a conditional integer value, it is required to control the dispersion property without moving λ_0. S is the ratio of the effective thickness showing birefringence in the liquid crystal layer, and can be changed in the range of $0 \leqq S \leqq 1$ depending on the applied voltage. The filled part in Figure 1 shows the area where can be realized by fixing λ_0. The gradient of the dispersion characteristic can be increased in this addition type, the single spectrum can be narrowed. Since the birefringence of the two liquid crystals having the dispersion property are added, it is not possible to obtain the property of 100% constant transmission.

Figure 4 is a subtraction type property with the optical axes orthogonal to each other. [4-6] In this figure, by adjusting $\Delta n_a d_a = \Delta n_b d_b$ at λ_0, the condition (1) $(\Delta n_a d_a - \Delta n_b d_b)/\lambda_0 = 0$ can be satisfied. When $S_a = S_b = 0$, the liquid crystal layer has no birefringence and is isotropic, the transmission can satisfy 100% in the visible region, and a large half-value width $\Delta\lambda = \infty$ can be realized. Here, the wavelength range in which the transmittance is 50% or more is defined as the half-value width $\Delta\lambda$. In addition, by combining S_a and S_b, the wavelength dispersion characteristic of the condition (2) can be changed within the difference between liquid crystal a and b while satisfying the condition (1), and the characteristic of the filled part in the figure can be realized. The flat property with respect to the wavelength λ indicates that 100% transmission can be achieved in all regions. Therefore, we examined the subtraction type.

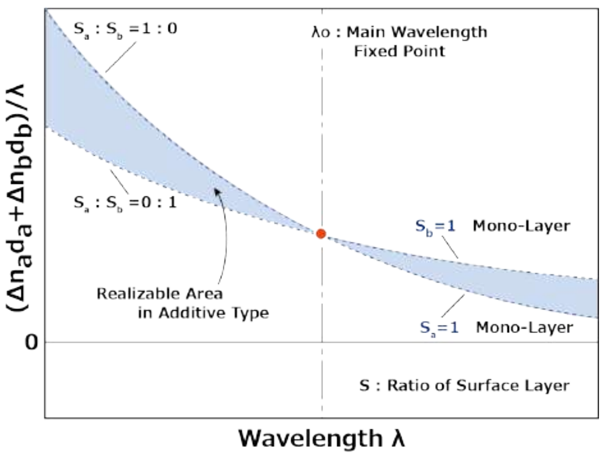

Figure 3 Stacked birefringent liquid crystal layer (addition type) .

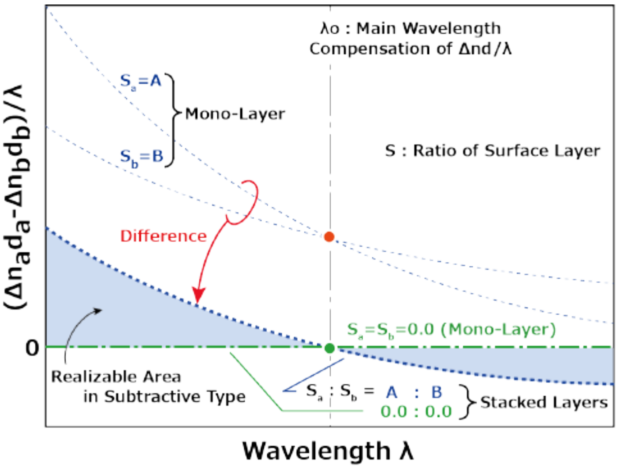

Figure 4 Stacked birefringent liquid crystal layer (subtraction type) .

3. Selection of liquid crystal with different dispersion property and TFLC property

In this section, we will examine the wavelength dispersion property with stacking liquid crystal layers of TFLC. In the device, the liquid crystals having different dispersion property are desirable. Figure 5 shows the wavelength dependence of birefringence Δn for some liquid crystals [7] . Since the absorption band is at a short wavelength, birefringence increases on the short wavelength region.

Figure 6 shows the property standardized by the wave number Δn/λ at λ = 550 nm in order to compare the dispersion property of the liquid crystals. From this figure, two types of liquid crystal, a: Biphenyl and b: Schiff, which have significantly different dispersion property, were selected and simulated.

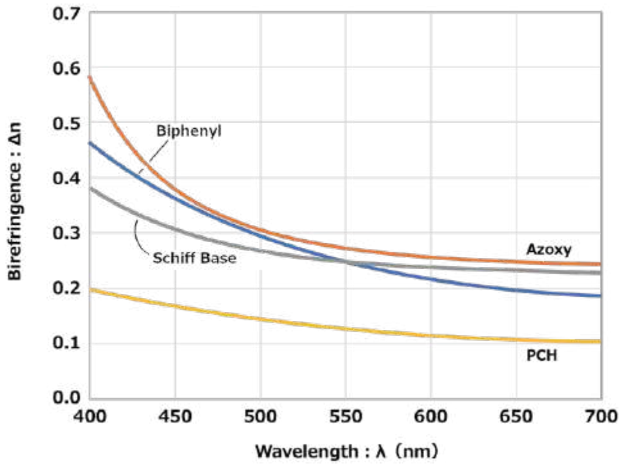

Figure 5 Δn dispersion property of liquid crystals.

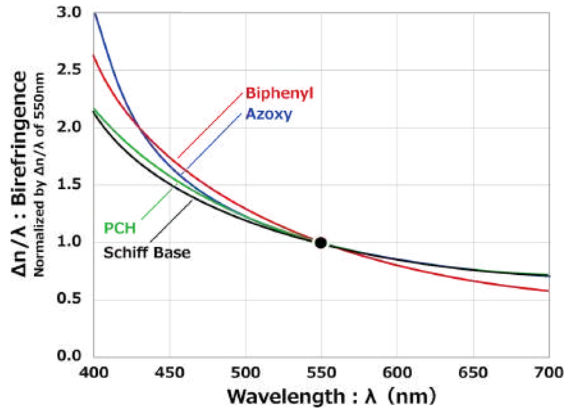

Figure 6 Normalized Δn/λ dispersion property of liquid crystals.

Figure 7 shows the wavelength dependence of birefringence when the liquid crystal layers of (a) the biphenyl-based and (b) the shift-based, which are aligned in parallel, are orthogonal to each other in the optical axis. The vertical axis shows the number of waves, which is directly linked to the transmission as shown in equation (1). The bar on the right side shows the transmittance qualitatively in shades. The main wavelength λ_0 is set to 550 nm. The S_a and S_b values in the figure indicate the surface layer value S of each liquid crystal layer. It has been shown that by controlling the S_a and S_b values, the slope of the dispersion property can be controlled while the number of waves at λ_0 is fixed at 0. Figure 8 shows the half-value width control of the transmittance. This figure is a diagram in which the vertical axis of the transmittance is converted by the equation (1) based on Figure 7, and it can be confirmed that the half-value width of 70 nm or more is obtained.

Considering the case where the main wavelength λ_0 is changed, it can be realized by adjusting Δn_a and Δn_b with the applied voltage according to $\Delta n_a d_a = \Delta n_b d_b$ satisfying the condition $(\Delta n_a d_a - \Delta n_b d_b)/\lambda_0 = 0$ that gives the maximum transmittance. The peak wavelength can be changed arbitrarily.

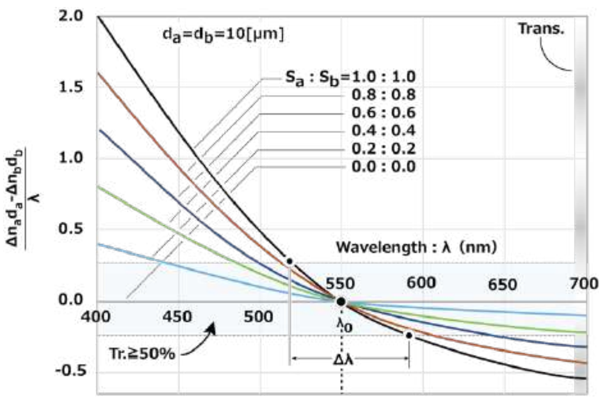

Figure 7 Voltage control of dispersion property.

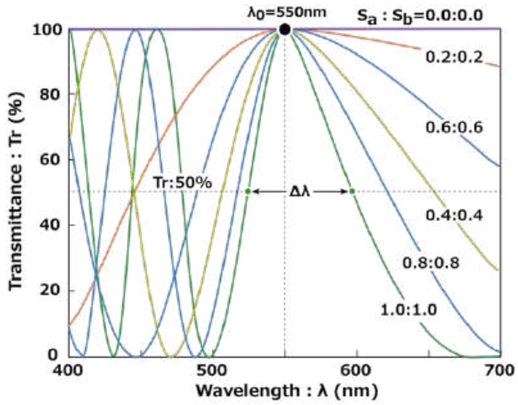

Figure 8 Voltage control with half-value width Δλ with fixed main wavelength λ_0=550nm.

Next, we tried to narrow the spectrum by stacking S-ECB elements. S-ECB means an stacking ECB with double layers discussed above. Figure 9 shows an example of the Lyot type device with three S-ECB. Assuming that the transmittance of each element is Tr1, Tr2, and Tr3, the transmittance of the three S-ECB elements stacked is given below.

$$Tr_0 = Tr_1 \cdot Tr_2 \cdot Tr_3 \cdots (2)$$

Figure 10 shows the transmission property of the S-ECB elements, and it was confirmed that a half-value width of about 23 nm can be obtained in a narrow band (Sa: Sb = 1.0).

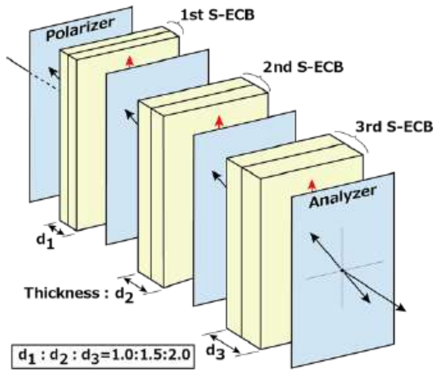

Figure 9 Lyot type TFLC with three S-ECB elements.

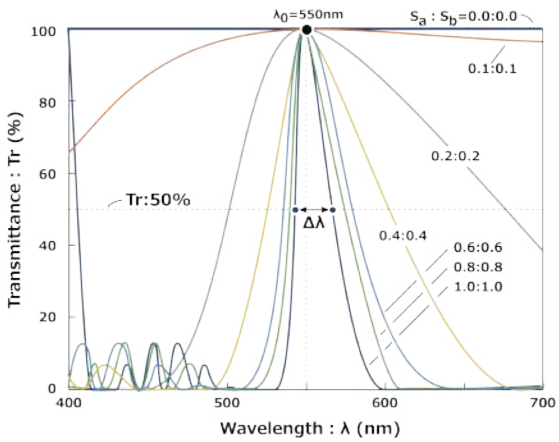

Figure 10 Property of TFLC with three S-ECB elements.

4 Conclusion

The liquid crystal shows function fully as an electronic display, and the transmission is controlled over the entire visible region by utilizing the birefringence property or the rotation of polarization. Further, as a TFLC, the spectrum is narrowed by utilizing the dispersion property of the birefringence. In this research, we constructed a method to arbitrarily control the dispersion property by combining the dispersion properties of the birefringence of multiple liquid crystal layers. This method realized that can independently and arbitrarily control the main wavelength λ_0 and the half-value width Δλ. This makes it possible to improve the controllability of TFLC and expand applications such as control of hue, brightness, and saturation of two-dimensional light sources.

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