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Abstract. A method of realizing a compact Fourier transform spectrometer is proposed in this work, which is based on the polarization interference in a single layer of birefringent liquid crystal (BLC). The continuous interference between the ordinary light and the extraordinary light is driven by a continuously adjusted electric field. Benefiting from the single-layer configuration with no moving parts, the spectrometer is easily miniaturized. The method to realize the spectrometer is theoretically analyzed and experimentally demonstrated by a layer of nematic BLC with a 100- μm thickness. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.53.7.074109](https://doi.org/10.1117/1.OE.53.7.074109)]

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1 Introduction

The Fourier transform spectrometer (FTS) has advantages of high throughput, high signal-to-noise ratio, and high spectrum resolution, which are widely used in material identification, chemical analysis, and environmental testing.¹⁻³ The conventional FTS is based on the Michelson-type interferometer, in which the light is split into two beams and the optical path difference (OPD) is modulated by the shift of a movable mirror.⁴ However, the movable mirror makes the system complex, bulky, and expensive. In the past decades, a lot of works have been focused on the developing of an FTS without moving parts.⁵⁻⁷

The spectrometer based on birefringent interference is a typical FTS without moving parts. A liquid crystal (LC) is a good birefringent material because of its large tunable refractive index, low driven voltage, and fast response, all of which have been widely researched in birefringent FTS.⁸⁻¹⁵ The primary methods of LC birefringent FTS are based on a Wollaston prism with spatial interference⁸⁻¹⁰ and a binary voltage-controlled LC stages with time interference.¹¹⁻¹⁵ For the spatial interference, the fringes are recorded by a detector array, which may increase the error due to the noise difference of the subdetectors. The time interference only needs a single detector and records the fringes by time delay. However, the LC stages configuration contains a lot of interfaces which will increase the reflection loss and result in a decrease of the sensitivity.

In this work, a method to realize a simple birefringent liquid crystal based Fourier transform spectrometer (BLC-FTS) with time interference is proposed. The BLC-FTS contains only one piece of LC, which is driven by a continuous voltage. By continuously changing the refractive index of the extraordinary light, the OPDs of the extraordinary and the

ordinary light are generated. The interference is obtained from the exiting beams by polarization selection. In this spectrometer, the reflection loss is low and it is easy to realize a compact spectrometer with few optical elements.

2 Method and Theory

The configuration of the proposed BLC-FTS is shown in Fig. 1. The collimated light propagates into the device, which is transformed into linearly polarized light by polarizer P1. The vector of P1 has an angle of α to the optical axis of LC, the linear light will be divided into ordinary light and extraordinary light after transiting LC. The refractive index of the extraordinary light is tuned by the voltage when transmitted through the LC with a thickness of d , which controls the phase difference of the two lights. The polarization axis of P2 is perpendicular to that of P1 in order to obtain interference between the ordinary light and the extraordinary light. The spectrometer has only a few coaxial optical elements which makes it compact and easily miniaturized.

To understand the theory of the BLC-FTS, the interference in the BLC is studied as below. When the incident light is unpolarized, half of the intensity will transmit through P1. For the ordinary light and the extraordinary light propagating to LC, the amplitudes are

$$\mathbf{E}_o = \mathbf{y} \sqrt{\frac{I_{in}(\lambda)}{2}} \sin \alpha, \quad (1)$$

$$\mathbf{E}_e = \mathbf{x} \sqrt{\frac{I_{in}(\lambda)}{2}} \cos \alpha, \quad (2)$$

where \mathbf{x} , \mathbf{y} are the unit x -axis and y -axis coordinate vectors for the LC, respectively. $I_{in}(\lambda)$ is the intensity of the incident

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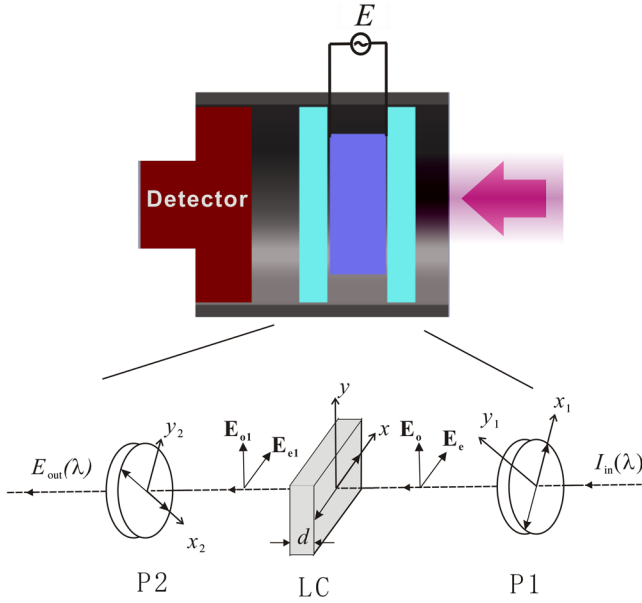


Fig. 1 The birefringent liquid crystal-Fourier transform spectrometer (BLC-FTS).

light and λ is the wavelength. α is the angle between vector of P1 and the optical axis of LC.

When the lights transmit through the LC with a thickness of d , the amplitudes are

$$\mathbf{E}_{o1} = \mathbf{E}_o e^{i\frac{2\pi n_o d}{\lambda}}, \quad (3)$$

$$\mathbf{E}_{e1} = \mathbf{E}_e e^{i\frac{2\pi n_e d}{\lambda}}, \quad (4)$$

where n_o, n_e are the refractive index of the ordinary light and the extraordinary light, respectively.

Polarizer P2 effectively changes the linear polarization basis set for light passing through it. The beam transmitted through P2 will have the combined contributions of the \mathbf{E}_{o1} and \mathbf{E}_{e1} components, each projected from the LC basis set (x - y coordinates) to the P2 polarizer basis set (x_2 - y_2 coordinate axes). Since only the x component of the P2 basis set is transmitted through P2, the projected amplitude of the transmitted beam is

$$E_{out}(\lambda) = \mathbf{x}_2 \mathbf{E}_{o1} + \mathbf{x}_2 \mathbf{E}_{e1}, \quad (5)$$

where \mathbf{x}_2 is the unit x -axis coordinate vector for P2.

The result from Eq. (5) yields the transmitted light intensity at the wavelength of λ which is

$$\begin{aligned} I_{out}(\lambda) &= |E_{out}|^2 \\ &= \frac{1}{2} |E_{in}(\lambda)|^2 \sin^2 2\alpha \left[1 + \cos\left(\frac{2\pi \Delta n d}{\lambda} + \pi\right) \right], \end{aligned} \quad (6)$$

where $\Delta n = n_e - n_o$ is the refractive index difference, which is the function of the driven electric field E . That is, $\Delta n = \Delta n(E)$ and can be continuously tuned by changing the driven

electric field. For a broadband incident light, Eq. (6) should be written as

$$\begin{aligned} I_{out}(E) &= \int I_{out}(\lambda) d\lambda \\ &= \frac{1}{2} \sin^2 2\alpha \int I_{in}(\lambda) \left[1 + \cos\left(\frac{2\pi \Delta n(E) d}{\lambda} + \pi\right) \right] d\lambda, \end{aligned} \quad (7)$$

which is in the form of the cosine Fourier transform, hence the spectrum of the incident light is

$$I_{in}(\lambda) \propto \int I_{out}(E) \cos\left[\frac{2\pi \Delta n(E) d}{\lambda} + \pi\right] d\Delta n. \quad (8)$$

3 Birefringent LC

Determining the incident light spectrum [Eq. (8)] requires analyzing how the refractive index difference of the BLC material (Δn) depends on the driven electric field E . In this article, the positive mixed nematic LC (from Xi'an Caijing Opto-Electrical Science and Technology Co., Ltd., Xi'an, China) is used as the BLC material. It is loaded in an LC box with an LC thickness of 20 μm . As illustrated in Fig. 1, the angle of $\alpha = 45$ deg, and the wavelength of the incident light is 633 nm. The detected intensity versus the voltage curve is shown in Fig. 2(a), which shows a non-linear interference.

The refractive index difference of the ordinary light and the extraordinary light is solved by Eq. (6) and the result is shown in Fig. 2(b). It shows that the refractive index difference decreases exponentially with the increase of the driven electric field. The maximum Δn is 0.234 when there is no driven electric field. Δn changes quickly when the electric field is ranged from 0.8×10^5 to 2×10^5 v/m. Based on this relationship, the spectrum can be solved by Eq. (8).

4 Spectrum Experiment

To demonstrate the BLC-FTS experimentally, an LC of 100- μm thickness is used in the system. The incident light is the He-Ne laser and the driven electric field is set as shown in Fig. 2(b). Figure 3(a) shows the intensity of the interference between the ordinary and extraordinary light as the driven electric field is varied. The interference intensity undergoes high frequency oscillation over the range of E where Δn changes most rapidly due to the fast change of the interference light phase. The inset shows the detail of the intensity curve marked in the red dashed box, which indicates a clear interference. In the process of cosine Fourier transforming by Eq. (8), the sampling of the OPD should be equally spaced. Hence, Fig. 3(a) shows that the sample space of the driven electric field is nonlinear, which satisfies the condition that the diffractive index difference space is 1.5825×10^{-3} ($\pi/2$ for phase difference).

The interference intensity is treated with Eq. (8), and the result is given in Fig. 3(b), which shows that the spectrum of the laser light is correctly determined with the full width half maximum (FWHM) of 10.5 nm. The FWHM represents the resolution of the spectrometer. For an FTS, the theoretical resolution is¹⁶

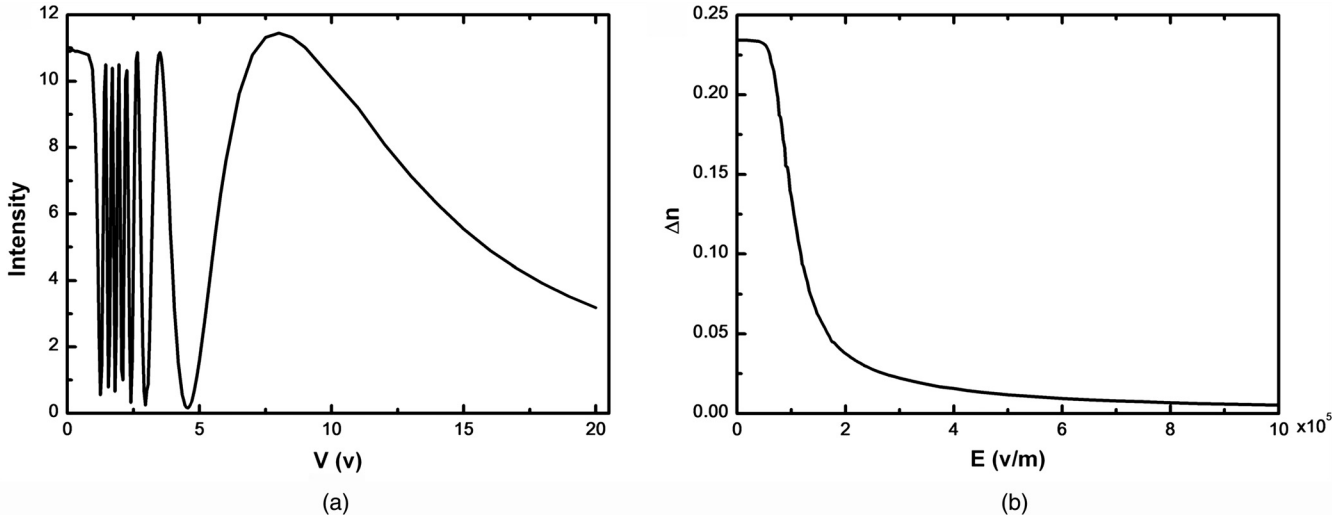


Fig. 2 (a) The output light intensity versus voltage curve with liquid crystal (LC) of 20- μm thickness. (b) The relationship between the refractive index difference and driven electric field.

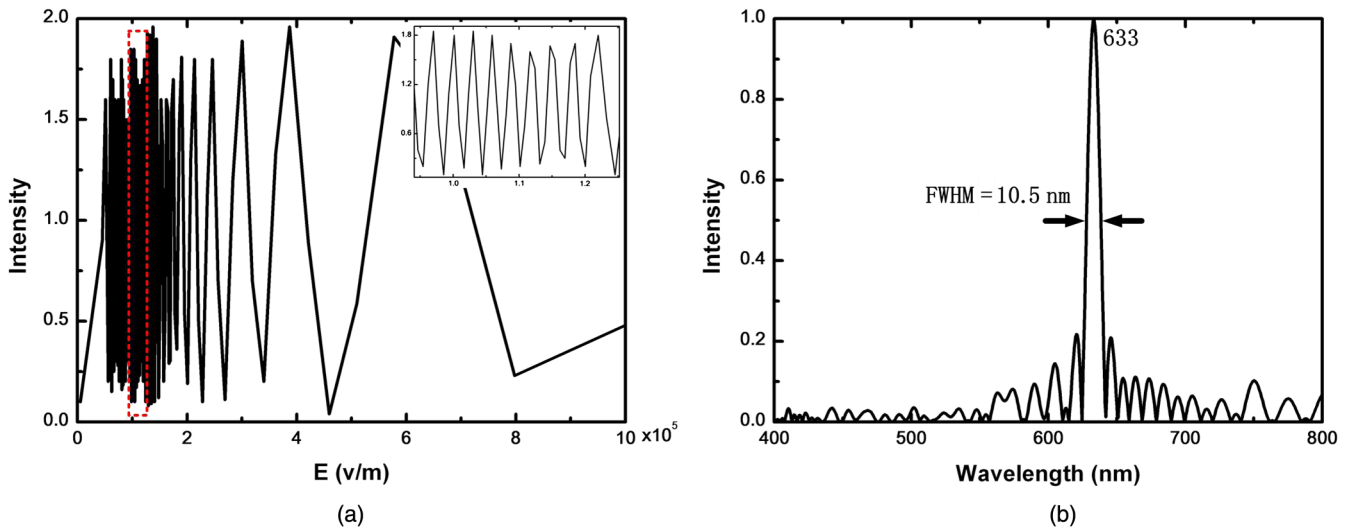


Fig. 3 (a) The fringes of the BLC-FTS with LC thickness of 100 μm . (b) The solved spectrum of a laser with the wavelength of 633 nm.

$$\Delta\lambda = \frac{\lambda^2}{2\text{OPD}_{\max}} \quad (9)$$

In the BLC-FTS, the $\text{OPD}_{\max} = \Delta n_{\max} d$. From Eq. (9), the theoretical resolution of the spectrometer with a 100- μm LC is 8.6 nm, which shows a slight deviation from the experimental result. It indicates that the proposed BLC-FTS has a good performance for spectrum detection. Based on the theory, the resolution of the BLC-FTS can be further improved by increasing the LC thickness.

Because the active optical element is a single thin-layered BLC which is coaxial to the thin film polarizers, the spectrometer can be integrated with the detector to form a compact spectrum device. In addition, when the detector is an array with multi-subpixels like the charge coupled device or complementary metal oxide semiconductor, the BLC-FTS will be a candidate for field-widened operation to

further enhance the throughput, such as for direct spectral imaging in the microscope.

5 Conclusion

In conclusion, a method to realize a simple FTS without moving parts based on a single-BLC interference is proposed. The theory of the spectrometer is discussed by analyzing the polarization interference of the BLC. With a positive mixed nematic LC material, the method is experimentally demonstrated. The spectrometer has the advantages of compact size and high throughput, which makes it easily be integrated into complex optical systems to carry out fast spectrum measurements.

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Biographies of the authors are not available.