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Abstract. The propagation of laser beam in a flow aligned nematic liquid crystal (NLC) and its interaction with liquid are illustrated in this letter. The effect of polarization and scattering on the transmitted power through the NLC under external perturbation flow is demonstrated here. It is found that the flow rate has a significant role in the modulation of refractive index of the medium leading to scattering and change in polarization. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3574767]

Subject terms: liquid crystal; birefringence; polarization; scattering.

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1 Introduction

Nematic liquid crystal (NLC) is one of the simplest anisotropic fluids which possess high molecular order even in the fluidic state. NLC usually consists of organic molecules of rodlike shape, about 10 to 15 Å in length. The average orientation of molecules is usually characterized by a unit vector, director $\mathbf{n}$.¹ Due to the optical anisotropy known as birefringence, properties of the transmitted optical beam such as polarization can be varied by applying a small perturbation. Using the above concept, NLC has been widely used in projection displays,² variable optical attenuator,³ polarization rotator,⁴ etc.

In this letter, we analyze the effect of liquid-light interactions when a collimated optical beam is transmitted through the NLC under different flow rates in a flow cell at room temperature.

2 Procedure

In order to analyze the change in the polarization under different flow rates, the flow cell was kept between crossed polarizers as shown in Fig. 1. The light source of He-Neon laser of wavelength 632 nm and NLC, 4-pentyl-4'-cyanobiphenyl (5CB, Merck Chemical Co) was used for the investigation. Flow cell of dimension 0.5-mm height and 1-mm width was fabricated using glass substrates of refractive index 1.52. The cell was connected to a syringe pump using silicone tubing with an outer diameter of 0.3 cm and an inner diameter of 0.2 cm.

A photodiode which is connected to a computer was used to detect the power variation. The flow cell was kept in such a way that the flow direction (x -axis) makes an angle of 90 deg with the polarization axis of the polarizer (y -axis). The NLC was injected into the flow cell and after the cessation of flow, a particular flow rate was given for 50 s and the output power was monitored. After switching off the flow, the transmitted power was monitored for 200 s. This was repeated for both low and high flow rates.

Experiments were performed by replacing the photodiode with a CCD camera and UV-VIS absorption spectrum of the liquid crystal was also taken to analyze the contribution of scattering and absorption on the transmitted power.

3 Results and Discussion

The UV-vis absorption spectrum shown in Fig. 2 indicates no significant absorption in the visible wavelength range and hence is negligible. It is expected that liquid-light interactions such as polarization and scattering contribute to the transmitted power variation. Figures 3(a) and 3(b) shows the variation of transmitted power with time for different flow rates. The change in the transmitted power is attributed to the refractive index modulation of the medium due to external perturbation (flow). For higher flow rates (35 to 50 ml/h), the response time is short when compared to lower flow rates (1 to 5 ml/h) and is of the order of seconds only, while the response time of the pump is 280 ms.⁵ This fact indicates that the response time is dependent on the flow rate.

The NLC in the flow channel can be considered as a birefringent medium with optic axis at an angle θ with horizontal axis (x). Therefore the transmitted light intensity emerging from the analyzer can be obtained using Jones calculus.

$$\begin{bmatrix} E'_x \\ E'_y \end{bmatrix} = J(A)J(NLC)J(P) \begin{bmatrix} E_x \\ E_y \end{bmatrix}, \quad (1)$$

where E_x, E_y, E'_x , and E'_y are the amplitudes of the incident and transmitted optical beam along the x and y directions, respectively. $J(A)$, $J(NLC)$ and $J(P)$ are the Jones vectors for the analyzer, the NLC flow cell, and the polarizer, respectively. When an optical beam passes through a birefringent medium of thickness d , it gets split into two rays with different refractive indices n_o and n_e with orthogonal polarization, and thus creating a phase difference. Therefore Eq. (1) becomes,

$$\begin{aligned} \begin{bmatrix} E'_x \\ E'_y \end{bmatrix} &= \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \\ &\times \begin{bmatrix} e^{i\varphi_x} \cos^2 \theta + e^{i\varphi_y} \sin^2 \theta & (e^{i\varphi_x} - e^{i\varphi_y}) \sin \theta \cos \theta \\ (e^{i\varphi_x} - e^{i\varphi_y}) \sin \theta \cos \theta & e^{i\varphi_x} \cos^2 \theta + e^{i\varphi_y} \sin^2 \theta \end{bmatrix} \\ &\times \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix}, \quad (2) \end{aligned}$$

where φ_x and φ_y are the phase differences along the horizontal (x), and vertical (y) axis respectively. The flow of NLC is complex when compared to ordinary fluids since the translational motion of the fluid affects the orientation order of the molecules.⁶ Upon the application of an external force (flow), the shear stress (σ) on the NLC changes the director

Fig. 1 Schematic diagram of the experimental set up used for the illustration of change in polarization with respect to flow rate.

Fig. 2 UV-vis absorption spectrum of NLC.

Fig. 3 Variation of transmitted power with time for low flow rates (left), and high flow rates (right).

Fig. 4 CCD images of the flow cell at different flow conditions (a) $Q = 1$ ml/h, $t = 50$ s (b) $Q = 0$ ml/h, $t = 100$ s, (c) $Q = 0$ ml/h, $t = 200$ s (d) $Q = 50$ ml/h, $t = 250$ s, (e) $Q = 0$ ml/h, $t = 350$ s, (f) $Q = 0$ ml/h, $t = 450$ s.

Fig. 5 Image contours of a laser beam transmitted through the flow cell under flow rate (a) 1 ml/h and (b) 50 ml/hr.

orientation.

$$\sigma = -pI - \frac{\partial F_d}{\partial \nabla n} \cdot \nabla n^T + \alpha_1 (nn : A) nn + \alpha_2 nN + \alpha_3 Nn + \alpha_4 A + \alpha_5 nn \cdot A + \alpha_6 A \cdot nn, \quad (3)$$

Where p is the pressure, I is the unit tensor, $\alpha_1, \alpha_2, \dots$ are the six Leslie viscosity coefficients, $\mathbf{n}$ is the director ($n^2 = 1$), A is the strain rate tensor, and N is the velocity of the director relative to the fluid. Ordinary index of refraction (n_o) is independent of the direction, while extraordinary index of refraction (n_e) depends on the orientation of the molecules with respect to the polarization axis of the incident optical beam (δ). Therefore at a particular flow rate shear stress causes a change in the orientation of the director (optic axis) which thereby results in the modulation of refractive index [birefringence, $\Delta n = n_e(\delta) - n_o$], Thus from Eq. (2), a change in birefringence creates an intensity modulation as

$$I = \sin^2 \left(\frac{\pi (n_e(\delta) - n_o) d}{\lambda} \right) \sin^2(2\theta) I_0, \quad (4)$$

The above relation of transmitted light intensity infers that birefringence of the NLC medium and the transmitted intensity depends on the orientation of the molecules at a particular hydrodynamic shear stress.

Figure 4 shows the CCD images of the transmitted laser beam for various flow conditions. At a flow rate of 1 ml/h, the beam gets expanded in the vertical direction and narrowed in the horizontal direction as it is transmitted through the flow cell [Fig. 4(a)]. After switching the flow off, within 200 s [Figs. 4(b) and 4(c)], the laser beam expansion is reduced. This effect is more pronounced for a high flow rate of 50 ml/h [Figs. 4(d) and 4(e), and 4(f)] which can be attributed to the beam fanning phenomena, a scattering effect.⁷ Here, without any preferred orientation, liquid crystal molecules exist in multidomains and the refractive index discontinuity at domain boundaries is expected to cause the scattering phenomenon. When a shear (flow) is introduced into the material, the refractive index modulation became more pronounced

resulting in the transmitted beam expansion. Therefore from Figs. 2 and 3, and 4 it can be inferred that a flow induced refractive index modulation is taking place resulting in both polarization change and scattering. Figures 4(a) and 4(d) are converted to contour plots as shown in Figs. 5(a) and 5(b), respectively, to analyze the intensity distribution of the expanded beam. It can be seen from Fig. 5 that the expansion of the beam along the major axis at a flow rate of 50 ml/h is approximately 1.6 times more than the expansion caused by 1 ml/h.

4 Conclusions

In summary, it can be concluded that an external force applied on the NLC results in the modulation of refractive index of the medium leading to polarization change and scattering. However, the contribution of each of these effects is yet to be identified. Our future work is targeted in this direction.

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