# Voltage Sensor with a wide Frequency Range using a Deformed Helix Ferroelectric Liquid Crystal

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**Abstract**—In this paper we propose a new approach to fiber optic voltage sensors via voltage-controlled Liquid Crystals (LCs), which would allow direct measurement of up to 400 kV/m electric fields at multiple points. In addition, the electro-optical behavior of deformed helix ferroelectric (DHF) liquid crystal in reflective mode is described and tested. The electrically controlled reflectance has been measured at sub-kilohertz driving voltage frequency for different polarizations of the incident light.

High-speed modulation using liquid crystals (LCs) is desirable for photonic applications, like real-time multi-point measurement and underwater sonar array systems [1-3]. Among various LC phases, nematic is widely used in displays [4, 5], since it bears the advantages of analog phase modulation and easiness to get uniform molecular alignment. However, nematic is known to have slow response time [6]. Also, this slow response gets worse if the LC layer thickness increases in order to obtain a $2\pi$ phase change at an infrared wavelength, say $\lambda$=1.55μm. Ferroelectric liquid crystals (FLCs) show very fast response time because their switching dynamics is based on the first-order response on an electrical field and a cone-confined molecular switching mechanism [7]. In particular, deformed helix ferroelectric (DHF) cells have been shown to be optically equivalent to a uniform biaxial layer under certain circumstances [8]. While most of the properties of DHF cells are obtained in transmissive mode [9,10], we explore a reflective configuration, which is a promising candidate of liquid crystal on a silicon (LCOS) display and fiber combined real-time sensing system[11, 12]. However, most of the FLC modes have limitations on these applications since the electrooptical response shows bistable switching [13] that cannot be applied to an analog modulator. Moreover, one of the critical issues in FLC devices is to obtain the alignment uniformity as well as optical quality of the FLC cells. In this paper, we apply DHF mode in a reflective configuration, which exhibits hysteresis-free switching regarding voltage. Photoaligning is the technique used in practice to achieve high alignment quality, which can realize controllable anchoring strength from the orientation layer on LC molecules and is also easy as a fabrication process. One of the remarkable characteristics in the dynamic behavior of DHF cells is the frequency dependency of response time. This property is observed widely and distinguishes DHF from other modes [14]. We propose a model to describe the frequency-dependent behavior, and show accurate agreement with experimental results.

Based on FLCs' ferroelectricity and their microscopic structural characteristics, the electro-optical switching of FLC directors is described as a smectic cone confined rotational switching driven by the torque coupled between the applied electrical field and the polarization in FLC molecules. Therefore, we use planar alignment configuration in which the electrical field is applied parallel with the smectic layer to switch the FLC molecules efficiently. While in this configuration, there occurs a delicate surface interaction between the alignment surface and the FLC molecules, which leads to the difficulty of uniform alignment. The photoalignment technique has been proposed to overcome these limitations [15, 16].

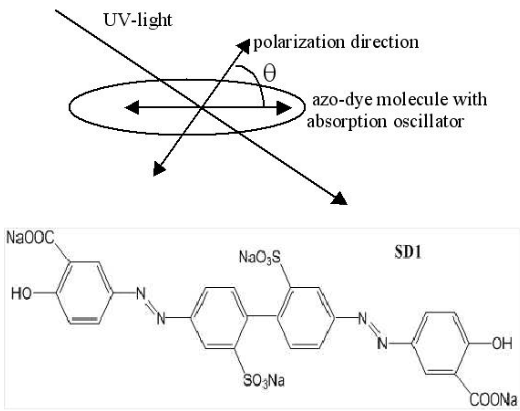


Fig. 1. Formula of the photochemical stable azo-dye SD-1. Above: the geometry of the effect.

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A sulfonic azo-dye, SD-1, is used for aligning an FLC molecule in DHF configuration with the formula shown in Fig. 1. One remarkable property of this azo-dye is the pure reorientation of molecular absorption oscillators perpendicular to UV light polarization without any photochemical transformations. Thus, the high photoalignment quality of FLCs onto azo-dye SD-1 layers can be achieved. The two substrates, one of which is coated with transparent electrode ITO and the other one is coated with a gold electrode for reflecting infrared light, are spin-coated with an SD-1 thin layer after treatment in an ultraviolet-ozone (UVO) cleaner for removing organic contaminants. Then the SD-1 thin layers are exposed to linearly polarized UV light to get the alignment orientation perpendicular to the polarization of projected light. The 5μm-thick layer of FLC material FLC-576 with the helix pitch 200nm (from P.N. Lebedev Physical Institute of Russian Academy of Sciences) is injected into the assembled cell.

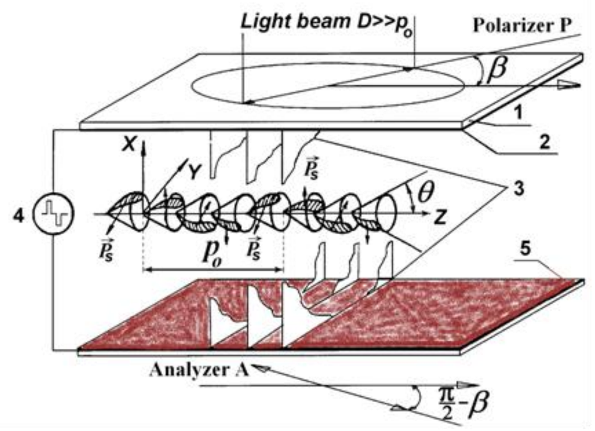


Fig. 2. Structure of smectic C* layers. 1-glass plate; 2-ITO with orienting layer; 3-smectic layers; 4-driving signal; 5-gold layer with orienting layer.

The geometry of DHF cells is shown in Fig. 2. The polarizer on the first substrate makes an angle, β, with the helix axis (z-axis) and the analyzer is crossed with respect to the polarizer. The FLC layers are perpendicular to the substrates and the cell gap is much larger compared with the helix pitch. When an electrical field is applied, the polarization, $P_S$, of the chiral smectic C phase is coupled and FLC director rotates around the z-axis with a cone angle of $2\theta_0$. The light reflectivity can be derived accordingly:

$$R = R_M \sin^2 2[\beta \pm \Delta\alpha] \cdot \sin^2 \frac{\pi 2 * d_{FLC} \Delta n_{eff}}{\lambda} \qquad (1)$$

Where $R_M$ is the reflectivity of the gold layer on the second substrate, $\Delta\alpha$ is the shift of helical axis due to applied electrical field $\boldsymbol{E}$, and $\boldsymbol{\Delta}_{neff}$ is the effective refractive index difference, which is also changing slightly with $\boldsymbol{E}$.

The electro-optical measurements have been performed with the set-up shown schematically in Fig. 3. He-Ne laser radiation with a wavelength 632nm passing through a linear polarizer normally incidents on the golden inner surface of the DHF cell at a certain angle between the light polarizing plane and the helix axis. The light beam reflected back from the golden mirror of the cell passes through the non-polarizing beam-splitter, which directs around 50% of the light onto the photo-detector. The analyzer is installed and aligned orthogonal to the polarization of the incident light in front of the photodetector.

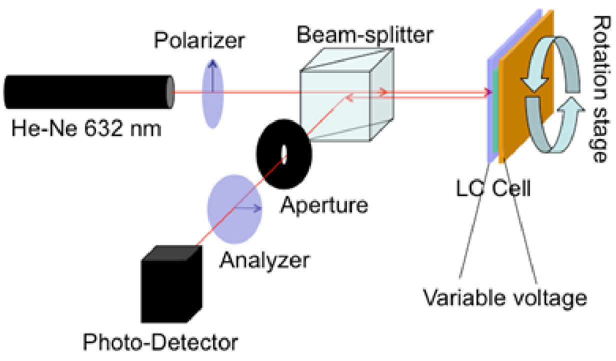


Fig. 3. Experimental setup for electrooptical measurements of DHFLC cells.

To analyze the reflectivity of the DHF cell, the driving signal is applied with variable amplitude and frequency. Fig. 4 shows the experiment result of voltage modulated reflectivity. The electrooptical response of a DHF cell is highly dependent on the polarization direction of incident light. When the polarizer is parallel to the helical axis, it shows a symmetrical V-shape response, which is suitable for a real display application. When the helical axis is around 15 degree shift from the polarizer, a near linear response regarding voltage can be achieved at a low electrical field. For aligning DHF cells, the anchoring strength of an orientation layer plays a critical role. The optimal anchoring energy is needed for high alignment quality, since the helix can be unwound when the anchoring strength is higher and the uniformity of helix direction cannot be achieved when the anchoring strength is lower. The experimental and theoretical study of the DHFLC reflective mode was first performed in this study. By the proposed method of explaining the influence of surface on electro-optical properties of the DHFLC, a satisfactory agreement between the theory and the experiment was obtained. It has been proved that the intensity of reflected light can be either proportional to the applied voltage or manifestly symmetrical regarding a zero voltage V-shaped response under certain conditions.

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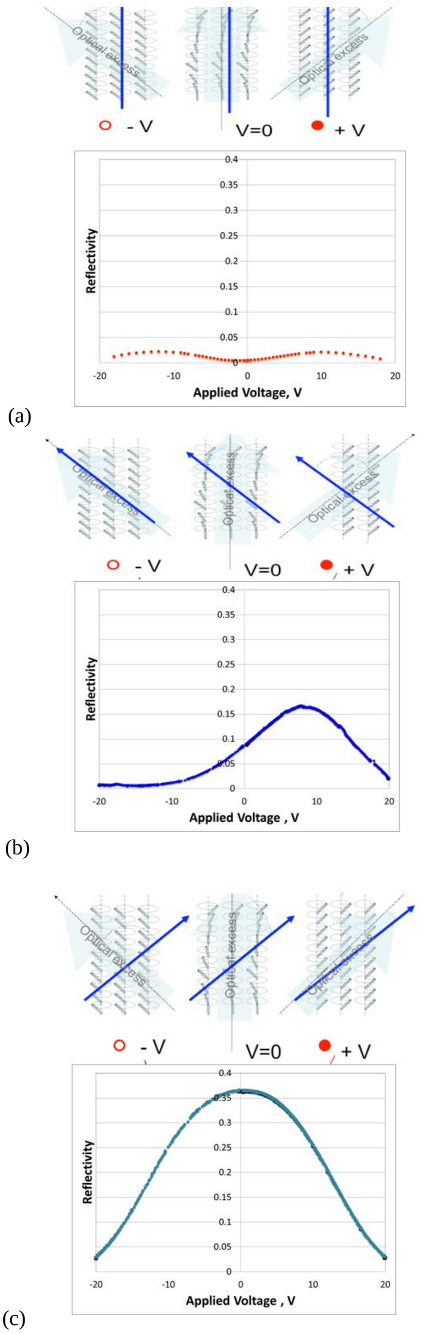


Fig. 4. Reflectivity on the square voltage amplitude applied to 5-μm-thick FLC-576 layer injected into the reflected DHFLC cell with (a) β = 0°, (b) 17° and (c) 45°.

In conclusion, we have presented a simple model to describe the reflection from a gold-coated DHFLC which, promisingly, could be applied in designing a practical device. It has also been demonstrated experimentally that this system exhibits a good linear electro-optical response when operated in reflection. A fast response to an electrical field, 175μs, is achieved, using a 5μm thick ferroelectric liquid crystal (FLC) layer driven by a 500Hz square wave. We believe that such a characteristic can be exploited in conjunction with an appropriate optical fibre setup to develop real-time multi-point voltage measurement and underwater sound detection or sonar array systems.

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