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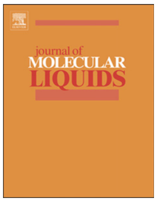

Phase modulation of mixed polarization states in deformed helix ferroelectric liquid crystals

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ABSTRACT

We study electro-optic properties of subwavelength-pitch deformed-helix ferroelectric liquid crystals (DHFLC) illuminated with partially polarized light. Theoretical results on the orientational Kerr effect and the modes of operation of such DHFLC cells are reviewed. By using the interferometry based approach to mixed-state geometric phases, we deduce the expressions for the total Pancharatnam and geometric phases of a partially polarized light wave passed through the DHFLC cell. We examine the effects of the polarization parameters on electric field dependence of the phases.

1. Introduction

At temperatures separating the phases of liquid and crystalline states certain compounds form orientationally quadrupolar ordered anisotropic liquids that are collectively called liquid crystals (LCs). Such liquids are characterized by LC orientational structures that appear to be extremely sensitive to both external fields and boundary (anchoring) conditions at the bounding surfaces (substrates). Generally, this sensitivity underlies all well-established modern liquid crystal technologies behind numerous exciting and successful applications of liquid crystal materials. In particular, since the optical properties of LCs are mainly determined by the LC orientational configurations and thus can be easily influenced, liquid crystals have been widely employed to modulate amplitude, phase, or polarization of light waves in space and time. Liquid crystal devices for light modulation are known as the liquid crystal spatial light modulators (SLMs) [1].

There is a variety of photonic devices used as building blocks of optical information processors and displays that require high-speed, low-power-consuming light modulation. Usually, for such devices, in addition to fast switching times, it is of crucial importance to have a 2π modulation so that the phase can be smoothly tuned from zero to 2π.

Nematic liquid crystals represent one of the most popular LC phase widely used in liquid crystal SLMs. However, nematic LCs are known to suffer slow response time. In addition, things will get worse when the LC layer thickness increases so as to obtain the 2π phase modulation. Much effort is, therefore, directed toward optimizing different LC electro-optic modes for the high speed light modulation.

Ferroelectric liquid crystals (FLCs) represent an alternative and most promising chiral liquid crystal material. This material is characterized by a very fast response time (a detailed description of FLCs can be found, e.g., in [2,3]) and equilibrium orientational structures forming helical twisting patterns where FLC molecules align on average along a local unit director

$$\hat{\mathbf{d}} = \cos\theta \quad \hat{\mathbf{h}} + \sin\theta \quad \hat{\mathbf{c}}, \tag{1}$$

where θ is the smectic tilt angle; $\hat{\mathbf{h}}$ is the twisting axis normal to the smectic layers and $\hat{\mathbf{c}} \perp \hat{\mathbf{h}}$ is the *c*-director.

The FLC director (1) lies on the smectic cone depicted in Fig. 1 with the *smectic tilt angle* θ and rotates in a helical fashion about a uniform twisting axis $\hat{\mathbf{h}}$ forming the FLC helix with the *helix pitch*, *P*. This rotation is described by the azimuthal angle around the cone Φ that specifies orientation of the *c*-director in the plane perpendicular

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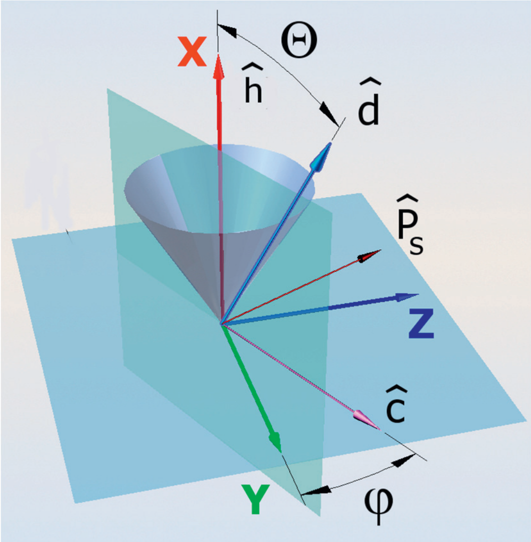

Fig. 1. Geometry of smectic cone. (Adapted from Ref. [4].)

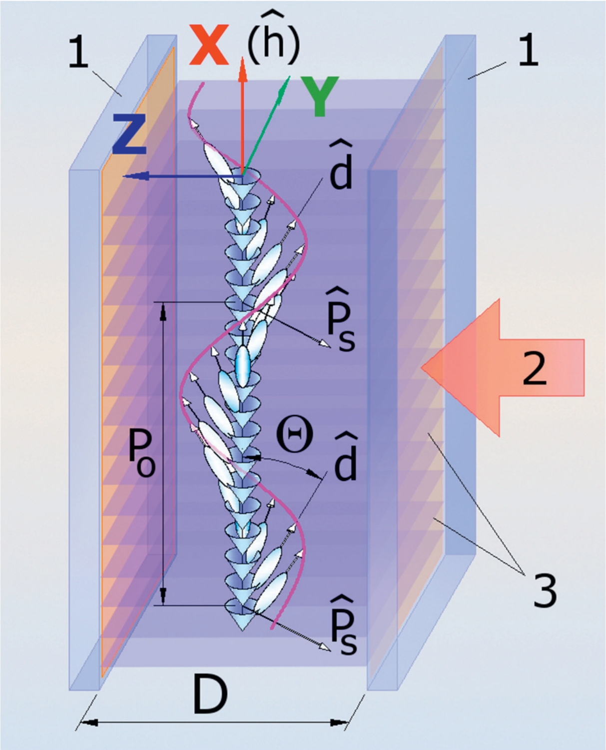

Fig. 2. Geometry of DHFLC cell. 1 – cell substrates; 2 – incident light beam; 3 – smectic layers. (Adapted from Ref. [4].)

to $\hat{\mathbf{h}}$ and depends on the dimensionless coordinate along the twisting axis

$$\phi = 2\pi(\hat{\mathbf{h}}\cdot\mathbf{r})/P = qx, \tag{2}$$

where $q = 2\pi/P$ is the helix twist wave number.

Fig. 2 illustrates the important case of a *uniform lying* FLC helix in the slab geometry with the smectic layers normal to the substrates and

$$\hat{\mathbf{h}} = \hat{\mathbf{x}}, \quad \hat{\mathbf{c}} = \cos\Phi \quad \hat{\mathbf{y}} + \sin\Phi \quad \hat{\mathbf{z}}, \quad \mathbf{E} = E \quad \hat{\mathbf{z}}, \tag{3}$$

where $\mathbf{E}$ is the applied electric field which is linearly coupled to the *spontaneous ferroelectric polarization*

$$\mathbf{P}_s = P_s\hat{\mathbf{p}}, \quad \hat{\mathbf{p}} = \hat{\mathbf{h}} \times \hat{\mathbf{c}} = \cos\Phi \quad \hat{\mathbf{z}} - \sin\Phi \quad \hat{\mathbf{y}}, \tag{4}$$

where $\hat{\mathbf{p}}$ is the *polarization unit vector*.

Fig. 2 shows a FLC layer of thickness D with the z axis normal to the bounding surfaces: $z = 0$ and $z = D$. This is the bookshelf geometry of surface stabilized FLCs (SSFLCs) pioneered by Clark and Lagerwall in Ref. [5] where they studied electro-optic response of FLC cells confined between two parallel plates subject to homogeneous boundary conditions and made thin enough (the thickness-to-pitch ratio, D/P, is typically less than unity) to suppress the bulk FLC helix.

This geometry also describes another limiting case of deformed helix FLCs (DHFLCs) as it was originally introduced in [6]. In this case, the FLC helix is characterized by a short submicron *helix pitch*, $P < 1$ μm, and a relatively large *tilt angle*, $\theta > 30$ °. By contrast to SSFLC cells, where the surface induced unwinding of the bulk helix requires the helix pitch of a FLC mixture to be greater than the cell thickness, a DHFLC helix pitch is 5–10 times smaller than the thickness. This allows the helix to be retained within the cell boundaries.

Electro-optical response of DHFLC cells exhibits a number of peculiarities that make them useful for LC devices such as high speed spatial light modulators [4,7-12], color-sequential liquid crystal display cells [13] and optic fiber sensors [14]. The approach to light modulation that uses the electro-optical properties of helical structures in DHFLCs with subwavelength pitch will be of our primary concern.

The effects caused by electric-field-induced distortions of the helical structure underline the mode of operation of such cells. Theoretical analysis of these effects was performed in [15,16] using the transfer matrix approach to polarization gratings combined with the method of averaging over the distorted FLC helical structure. The key result is that optical properties of DHFLCs with subwavelength pitch (the helix pitch is less than the wavelength of light) can be described in terms of the effective dielectric tensor that gives the principal values and orientation of the optic axes as a function of the applied electric field. Biaxial anisotropy and rotation of the in-plane optic axes produced by the electric field can be interpreted as the *orientational Kerr effect* [10,11,16].

Most of the FLC modes, however, suffer the optical axis switching problem that impede their use in phase-only modulation devices. The problem is that the electrically induced rotation makes the optic axes sweep in the plane of the cell substrate producing undesirable changes in the polarization state of light. One of the approaches proposed in order to get around the optic axis switching problem is based on the orientational Kerr effect in a vertically aligned DHFLC with subwavelength helix pitch [10,11].

An important point is that all the above-mentioned studies deal with the case of linearly polarized illumination where the incident beam is fully polarized. In this paper, we will go beyond this limitation and systematically examine the electro-optic behavior of the planar aligned DHFLC cells illuminated with partially polarized light. The limiting case of unpolarized light was recently studied in Ref. [4] as the way to obtain the response insensitive to the effect of electric-field-induced rotation of in-plane optical axes which was found to be