ITO Electrodes

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The very common electrode in the LC cells, i.e., ITO, is well known for its refractive index modulation property. In the regimes of low addressed electrostatic potential and visible optical power, it can act quite semiconducting due to the charge carriers' redistributions with a low density in the laser beam spot.

A challenge was the understanding of the sources of the SPR effect in the NLC cells; it was found that the electron-hole-pair production and subsequent transport can happen in the ITO thin layer in addition to the orientant, where the residing charge carriers in the beam spot can be effectively neutralized due to the photo-induced low conductivity. In the semiconducting operating mode of the ITO layer, a fringe electric field with its tangent element to the LC confining surfaces (equipped with ITO) was induced which results in the LC director field realignment parallel to the cell surfaces (irrespective of the sign of the dielectric anisotropy), hence the SPR effect.

Keywords: ITO Electrode, Photorefractive Effect, Nematic LC

1. Introduction

The surface photorefractive (SPR) effect describes a change in refractive index near the surface of a material owing to an optically induced redistribution of electrons and holes. An optically induced refractive index modulation due to nonuniformly photoinduced charge carriers generation and migration was first discovered in ferroelectric materials at a laser beam focus region [1][2]. In inorganic materials, the photorefractive index change is associated with an internal space–charge electric field, E_{SC}, known as Pockels effect [3].

In pure (undoped) nematic liquid crystal (NLC) cells, the SPR effect is realized as a director field reorientation driven by a nonuniform electric field of photogenerated-charge carriers under the action of a visible light beam, which was, for example, manifested in aberrational patterns formation and characterizations [4][5]. In liquid crystal (LC) cells, it is typically specified by the tangent element of the modulated electric field at the LC interfaces with the cell surfaces [5]. Indium-tin-oxide ([In_2O_3:Sn], ITO) coating of the glass plates of LC sandwich cells is often used as a conducting transparent electrode for electro-optic switching. The related conductivity of ITO normally excludes tangential components of a static electric field, which are easily compensated by mobile charge carriers that redistribute in the conducting layer. It is thus puzzling, at first glance, that ITO layers can nevertheless serve as semiconducting photosensitive layers producing tangential electric field components that may lead to specific local reorientations of the nematic LC director. Thanks to the photosensitive semiconducting behavior of the ITO layer, the SPR effect can be exploited for beneficial applications in electro-optics. In this review, the physical background that solves this apparent paradox is discussed.

The SPR effect in the NLCs was first attributed to the bulk photogenerated-charge carriers separation (due to the bulk drift and diffusion of the photogenerated-charge carriers in the static electric field) leading to a photoconductivity at moderate light intensities. The mechanism was suitably intensified in doped NLCs [6–8] supplied with photo-charge producing agents, where the lifetime of the optically excited states of ionic carriers (generated from bimolecular dissociation) was desirably enhanced [6]. The static nature of the space–charge field was verified in the self-diffraction investigations of nematic cells [6][7]. Later on, the theory of the bulk SPR effect in NLC cells was modified by taking the strong anchoring condition at the cell surfaces into account [9].

Diffraction-grating studies in the cells filled with homeotropically aligned NLC suggested that the observed SPR effect is most likely due to the photo-induced charge carriers' modulation at the interfaces of the orientants (aligning layers) and the LC, rather than being dominated by the ions' separations and migrations in the undoped LC bulk [10]. This hypothesis was developed as the modified electric field can rotate the director field form initial (homeotropic) alignment in the bulk, as well as at the aligning surface (despite the pre-defined anchoring condition as being initially normal to the cell surfaces). The speculation was that the tangent element of the surface–charge field is able to change the anchoring properties of the aligning surface, and hence the easy axis of the anchoring [10].

Further investigations confirmed the dominancy of the surface charge modulation in the photorefractive effect observed in pure NLCs, while rejecting the hypothesis of anchoring tuning at the LC cell surfaces [11]. It was understood from a diminished threshold voltage verified selectively at the anode in the laser on state, and hence decreasing the effective operating DC voltage [11][12][13]. This effect was realized at the double layers of polymer-LC and transparent electrode (ITO)-polymer in pure LC cells [11][13] illuminated with an appropriate wavelength. The alternating mode, AC, does not support charge carriers accumulation in the ITO electrode, hence the SPR effect [14]. An optically induced reduction in the surface charge carriers densities contributing to the screening of the biased DC electric field was confirmed at laser on-state [13] due to the photogeneration of charge carriers. On the other hand, in photocurrent measurements, the key role of the transparent conducting oxide (TCO) electrode, i.e., ITO, was verified where the SPR effect was seen in all types of undoped LC cells treated or non-treated with an alignment layer [13]. In doped NLCs with dye, the director field alignment in the SPR effect can be controlled by dye deposition on a nonphotosensitive aligning surfaces (of UV-irradiated para-PVCN-F orientant) [15]. In doped NLC mixtures (despite undoped matrices), the asymmetry of the aberrational patterns induced by the self-action of the light beam are decreased due to the interaction of the light field with the LC director field [16].

It was also experimentally shown that equipping a photoresponsive NLC cell with an ITO electrode can change the entity of the formed topological defects at the laser exposure spot from hyperbolic [17] to radial (with and without polymer coating as an anchoring agent) [18], while the impact of the ITO layer on modifying the electric field distribution in such LC test cells as a result of the induced space–charge field, was verified and simulated in an alternative work [19].

2. ITO Electrode as the SPR Effect Source in the Pure NLC Cells

Photocurrent measurements in the pure liquid crystal cells addressed with a DC voltage verified the SPR effect in the ITO thin film [13] acting as a semiconducting electrode lit by an appropriate optical wavelength. Test cells filled with an NLC (i.e., ZhKM-1277 nematic matrix) with a thickness of $d =$ 50 μm confined by ITO equipped glass plates were exposed to a solid state laser (λ = 473 nm) with a beam waist of about 100 μm. The charge flow in the external circuit driven by the laser beam illumination on the LC cell was obtained as Q_{ph} ≈ 7.5×10^{-11} C, whereas the screening charges in the laser exposure region estimated as Q_{sc} ≈ 2×10^{-14} C. If Q_{ph} was associated solely to the photogenerated mobile charges due to optical transitions. Since pair-production happens, the value of Q_{ph} indicates that the photogenerated-charge carriers are large enough to neutralize the screening charges in the beam spot [13].

Here, the photo-induced current density flow in the external circuit is dominated by the photogenerated electrons transported under the action of the modified static electric field, (see Section 3), as $J_{drift} = Q_{ph}\mu E =$ 3.9 nA/m^2 (where the reduced electric field E was obtained from the reduced voltage V (equal to 0.65 V [13]) divided by the cell thickness d. Here, μ is the charge carrier mobility assumed equal to 40 cm^{-2}V^{-1}s^{-1}). With the assumption of a Gaussian profile for the screening charges at the anode (photogenerated holes) with the same full width at half maximum (FWHM) as the beam width, for example, the diffusion current can be calculated from $J_{diff} = -D\frac{\partial Q_{sc}}{\partial x}$ in one dimension (1D), supposed along the *x*-direction, where D is the diffusion constant ($= \frac{K_B T}{q}$, K_B is the Boltzmann constant, T is the temperature, and q is the electric unit charge), in a cross section through the beam center, which gives the maximum diffusion current with the same order of magnitude as the drift current for the photogenerated positive charge carriers before going to the recombination process.

Charge carrier photogeneration can happen in the ITO layer when shone by a laser beam with an appropriate wavelength in the visible range, as discussed in Section 2.1. Since ITO is an n-type semiconductor, the SPR effect is more effective at the ITO electrode connected to the anode (positive) polarity of the battery. The SPR effect can be further enhanced by a charge carrier photogeneration and diffusion in the alignment layers [11][13].

Photoinduced modulation of the conductivity of the ITO electrodes can support the occurrence of the SPR effect. While the Burstein–Moss (B–M) effect can be an important factor in the low effective voltage regime (in the ITO layer) by controlling the conductivity of the ITO as for example explained for the NLC cells with photoresponsive substrate [19].

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