A model for the study of the optical transmission dynamics of liquid crystals dispersions under the influence of an electric field

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Abstract. In this paper, mathematical models are developed to correlate the time-resolved optical transmission experiments of liquid crystals dispersion devices under the influence of an electric field. The dispersion of liquid crystal in the confining matrices is supposed to be composed of identical spherical microdroplets containing the nematic liquid crystal phase. It is proposed that the confining surface induces the formation of a gradient of the torsional molecular velocities (switching velocities) in the response to an electric field or relaxation by the removal of an electric field, along the radius of the liquid crystal microdroplets. A method is proposed to determine the probability density function of the switching velocities. Applying the Laplace transform, the time-dependent functions for the optical transmission behavior of the liquid crystal dispersions are obtained. The model was applied to the study of the dynamics of glass dispersed liquid crystals devices, showing good correlation with the experimental data.

1 Introduction

Liquid crystals (LC) devices have attracted much attention for their special optical properties and nowadays they are used in many technological applications. A particular case of such devices are those based on liquid crystals dispersions; the polymer and gel-glass dispersed liquid crystals (PDLC and GDLC, respectively) have been widely developed in the past decade oriented to practical applications, and are still under study. These systems are also interesting from the basic research point of view, for instance for the study of the molecular interactions between surfaces and liquid crystals [1,2]: the surface effects are relevant at the level of micro-dispersions, due to the large surface-to-volume ratio at this scale. In GDLCs, the confining hybrid organic-inorganic matrix is prepared by the sol-gel technique, allowing the easy tailoring of the surface in contact with the LC. This is an interesting feature of the GDLCs, for the study of the LC-matrix surface interactions [3].

In LC dispersions devices, the electro-optical behavior (opaque/transparent states) is due ultimately to the molecular motion of the LC molecules in order to align their molecular axis with respect to the direction of the applied electric field, or to the disaligning when the electric field is turned off. The opacity is due to scattering of light. The minimum opacity, when the electric field is applied, is reached by refractive index matching between the aligned LC and the encapsulating matrix. The resolution in time of such variation of transmittance allows the study of the molecular motion of the confined LC.

The transmitted light in a scattering medium can be expressed as [4]

\[ I = I_0 e^{-T(\lambda)d}, \] (1)

where \( I_0 \) is the intensity of the incident light, \( T(\lambda) \) is the turbidity that is dependent on the wavelength of light \( \lambda \), and \( d \) is the depth of the scattering medium or film thickness (see fig. 1). The turbidity is given by

\[ T(\lambda) = N_s \sigma(\lambda), \] (2)

with \( N_s \) as the number density (concentration) of scatterers (microdroplets) and \( \sigma(\lambda) \) is the scattering cross-section. Using a monochromatic source of light for the experiments, the unique fact that affects to \( \sigma(\lambda) \) is the orientation of the LC molecules. Therefore, the turbidity can be used as an optical variable to study the switching dynamics, due to its direct proportionality to the scattering cross-section.

The electro-optical dynamics of LC dispersions can be expressed in terms of turbidity \( T(t) \) as

\[ T(t) = T_{\text{min}} + (T_{\text{max}} - T_{\text{min}})(m + n \cdot f(t)), \] (3)

where \( T_{\text{min}} \) and \( T_{\text{max}} \) are the minimum and maximum turbidities, respectively, \( f(t) \) is a decay function of time \( t \). \( m = 0 \) and \( n = 1 \) describes the response process to an electric field. \( m = 1 \) and \( n = -1 \) describes the relaxation process, when the electric field is removed.
In this paper a model is proposed to determine the gradient of switching velocities along the radius of the encapsulated microdroplets of LC. The probability density function of the switching velocities is obtained with the proposed model by assuming a spherical geometry of the microdroplets. By means of the Laplace transform, the time-dependent function for the variation of the turbidity of LC dispersion devices is derived. The work is focused on obtaining a function $f(t)$ based on the existence of a distribution of characteristic velocities $k$ inside the droplets, analogously to the molecular velocity in a laminar flow, where a gradient of velocities is observed as a function of the distance from the surface. The elastic constants of the LC involved in the reorientational processes induced by an electric field are implicitly related to the molecular velocities of the LC. The emphasis of the present work, however, is set on the distribution of velocities induced by the surface of the confining matrix, where the LC is allocated. Mathematical models are developed to give a phenomenological description of the time variation of the turbidity of LC dispersions, regardless of the dependence of the molecular velocities on the elastic constants of the LC. The developed model shows good correlation with the experimental time-resolved turbidity of GDLC devices.

2 Experimental details

Three confining matrices were prepared, having different chemical environment of the porosity where the LC molecules will be allocated. The inner pore surface of the silica matrices was functionalized with Me (methyl, CH$_3$) groups, with Me/Si molar ratios of 0.3, 0.5 and 1.0 for samples Me030, Me050 and Me100, respectively.

The GDLC devices were prepared following the procedure described elsewhere [8]. The LC used for the preparation of the samples was the nematic 4-pentyl-4′-biphenyl-carbonitrile (ABCR, Germany). The films were deposited by spin coating at 2000 rpm on transparent conductive ITO-coated glasses (Chomerics).

The film thickness was measured with a Mitutoyo Surftest SV-3000 surface roughness testing system.

The time-resolved turbidity experiments were carried out in the experimental set-up described in fig. 1, using a He-Ne laser ($\lambda = 632.8$ nm) as light source. The system has a $f/100$ collection optics [4]. AC sinusoidal voltage was applied at high frequencies (25 kHz), to avoid matrix conductivity effects [9]. All the measurements were carried out at a temperature of 298 K.

Microscope photographs were taken by a PCO 1600 camera attached to a Leica BMRM optical microscope equipped with polarizers at 100× magnification.