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Effect of spherical magnetic particles on liquid crystals behavior studied by surface acoustic waves

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ABSTRACT

The effect of spherical magnetic particles (Fe_3O_4) on liquid crystals (6CHBT) behavior and structural changes in electric and weak magnetic fields was studied by means of the attenuation of surface acoustic wave (SAW) of frequency 30 MHz propagating along ferronematic liquid crystals. Three low volume concentrations ($\Phi = 1 \times 10^{-5}$, 1×10^{-4} and 1×10^{-3}) of spherical magnetic particles were added to liquid crystal during its isotropic phase. In contrast to undoped 6CHTB the distinctive SAW attenuation responses induced by both electric and magnetic fields in studied ferronematic liquid crystals below Fréedericksz transition have been observed suggesting both structural changes and the orientational coupling between magnetic moments of magnetic particles and the director of the liquid crystal. The geometrical re-ranking of magnetic particles was registered only for some orientations of magnetic field. Observed results confirmed the significant influence of the presence of magnetic particles on the structural properties and following behavior of 6CHTB.

1. Introduction

Doping process of liquid crystals (LCs) can prepare novel materials that can have very interesting properties which are absent in original LC substances. LC suspensions containing nanoparticles have registered additional great attention for many practical applications such as nanosensors, liquid crystal display industry, optical processing, biosensors, photonics and magneto-optics. New applications are in need of new materials with exotic properties and new technologies [1]. It is already known that ferroelectric particles have the strong effect on optical and dielectric properties of the nematic matrix. The increase of birefringence and dielectric anisotropy of the nematic matrix by the particles is caused by a giant dipole moment of ferroparticles that change the intermolecular interaction in the LC matrix and give a direct contribution to the value of effective dielectric constants of the matrix. Introduction of the particles leads also to the decrease of driving voltages, increase of the reflection contrast and the steepness of the transition [2]. Carbon-based nanostructured materials and their relationship with liquid crystals (LCs) are another topic in current research. It is worth mentioning the recently described connection between graphene oxide and liquid crystals [3] as well as the highly active topic of LC structures doped with carbon nanotubes (CNTs) and the possibility of reorienting them with external fields [4].

Next of such materials could be also the suspension of magnetic particles in nematic liquid crystals. Stable colloidal suspensions of monodomain ferromagnetic particles in nematic LCs in small concentrations, called ferronematics, newly attract noticeable interest because their response to an external magnetic field oversteps substantially that of pure nematics. Ferronematics are a manifestation of an idea that doping liquid crystals with fine magnetic particles may enhance their sensitivity to magnetic fields. The most essential feature of these systems is an orientational coupling between the magnetic particles and the liquid crystal matrix that can cause the realignment of rotation inside ferronematics suspension. The applied magnetic field namely changes the orientation of magnetic particles and due to the coupling between magnetic particles and liquid crystal molecules the director follows it.

In spite of the known fact that LCs can be orientated under magnetic or electric fields due to their anisotropic properties, the small value of the anisotropy of the diamagnetic susceptibility causes that magnetic fields necessary to align pure liquid crystals have to reach rather large values ($B > 1$ T). The idea of doping them with fine magnetic particles was then introduced in an effort to improve the magnetic susceptibility of liquid crystals [5]. It was predicted that a rigid anchoring $\mathbf{m} /\!/ \mathbf{n}$, where the unit vector $\mathbf{n}$ (director) denotes the preferential direction of the nematic molecules and the unit vector $\mathbf{m}$

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denotes orientation of the magnetic moment of the magnetic particles, would result in ferromagnetic behavior of the nematic matrix. Subsequent experiments confirmed the existence of considerable both orientational and concentrational effects in liquid crystals doped with magnetic particles as well as the fact that the essential feature of these systems is a strong orientational bonding between magnetic particles and the liquid crystal matrix [6–9]. However, the properties of magnetic particles significantly depend on their size, shape and structure. So far the magnetic particles have established a range of applications.

Acoustic (ultrasonic) methods are a useful tool for the characterization of LC elastic and viscous parameters especially in the vicinity of phase transitions [10]. Concerning the utilization of surface acoustic waves (SAWs), they were used to determine the viscosity distribution in LC layer depending on applied electric field and to study the effect of structural transformation in LCs under acoustic oscillations [11–13]. The SAW can be also utilized for the LC realignment based on the acousto-optic effect, as the SAW-driven LC light shutter [14] or SAW sensor [15].

In this contribution we present, after the first introductory results [16], the utilization of SAW to study the effect of spherical magnetic particles on the nematic LCs behavior induced by electric and low magnetic fields, to study the corresponding orientational coupling between magnetic particles and liquid crystal matrix as well as structural changes initiated by applied electric and magnetic fields. When the SAW propagates along the crystal delay line that is in contact with liquid crystal, SAW radiates a longitudinal wave into liquid giving rise to the propagation loss. This mode conversion is caused by the surface vertical displacement of SAW [17]. Other one or two types of propagation modes can be present due to the fact that the surface acoustic waves in crystals are shear waves. However, when the wavelength of SAW in the LC far exceeds the thickness of the LC layer, only one of these modes, in propagation direction, can contribute to the major losses [11]. So the interaction of both modes of SAW in investigated ferronematic LC layers gives rise or decrease of acoustic attenuation when LC molecules or magnetic particles change their orientation due to the changed external conditions.

2. Experimental details

The synthesis of spherical magnetic nanoparticles was based on co-precipitation of Fe^{2+} and Fe^{3+} salts by NH_4OH followed by dissolution of $FeSO_4{\cdot}7H_2O$ and $FeCl_3{\cdot}0.6H_2O$ in deionized water and then heated to 60 °C to obtain Fe_3O_4 precipitate. The nematic samples studied here were based on the thermotropic nematic 4-(trans-4-*n*-hexyl-cyclohexyl)-isothiocyanato-benzene (6CHBT). 6CHBT is an enantiotropic liquid crystal with a low melting point and high chemical stability. The temperature of the nematicisotropic transition (clearing point) of the LC is at temperature T_{N-I}=42.8 °C. The nematic samples were subsequently doped with a magnetic suspension consisting of Fe_3O_4 particles (diameter $d \sim 10$ nm) coated with oleic acid as a surfactant. The doping was simply done by adding this suspension, under continuous stirring, to the LC in the isotropic phase [8,9]. Due to the small volume concentrations of the magnetic particles ($\Phi = 10^{-5}$–10^{-3}) and surfactant, interparticle dipole–dipole interactions can be avoided in the prepared ferronematic samples. The homogeneity and stability of the samples were verified by optical microscopy and by dielectric measurements, indirectly [8].

The experimental arrangement is illustrated in Fig. 1 including the detail configuration of delay line with LC cell. The SAWs of fundamental frequencies 10 and 20 MHz were generated using one of the interdigital transducers (IDT), evaporated on the $LiNbO_3$ delay line, using the Pulse Modulator and Receiver – MATEC 7700. The second transducer was used as receiving of SAW. However, further harmonic frequencies 30, 40, 50,... MHz could be used, too. The acoustic attenuation was measured using Matec Attenuation Recorder 2470A. The SAW of frequency 30 MHz appeared the most sensitive for the registration of any structural changes which are in progress in LCs due to the application of electric or magnetic fields. The samples of LCs with thickness ensured by the spacer ($D \sim 100$ nm) were located on the center of the acoustic delay line and sandwiched between delay line and glass plate, both coated with gold evaporated electrodes.

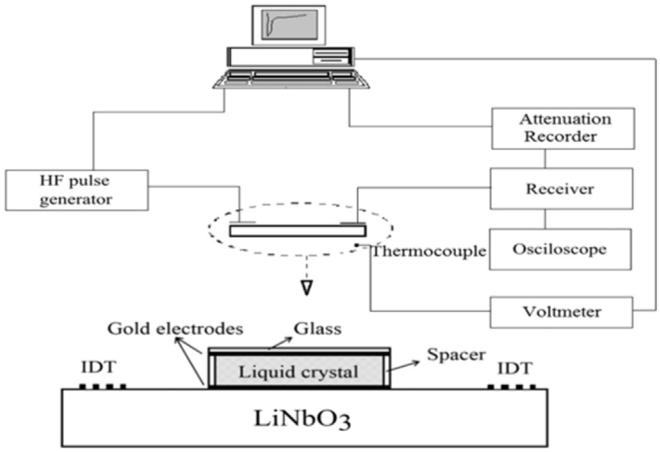

Fig. 1. Schematic illustration of experimental set up including detail arrangement of LC cell on $LiNbO_3$ delay line for SAW investigation.

3. Results and discussion

Structural changes in LCs were monitored using the acoustic attenuation measurements of SAW propagating along the interface between the $LiNbO_3$ delay line and LC cell. The used low SAW power should eliminate the role of SAW on LC reorientation. The initial intrinsic arrangement of LC was supposed to have a planar alignment when the director **n** was parallel to electrodes (Fig. 2a) and electric field was then applied perpendicular to them. The applied electric field turned the director to its direction so that LC molecules changed orientation into direction perpendicular to the surface of electrodes and SAW attenuation subsequently changed. The magnetic field could be applied in directions both parallel and perpendicular to electrodes, either to stabilize the initial orientation of LC molecules as well as magnetic particles or to highlight the turning effect of electric field. However, it follows from the viscosity distribution measurement [13] that the reorientation of molecules depends on the electric field intensity and that molecules change then the orientation gradually and start at the center (Fig. 2b).

Fig. 3 shows the effect of applied voltage on the SAW attenuation in 6CHBT doped with spherical Fe_3O_4 ($\Phi = 10^{-4}$) for the application of various (increasing) voltages in two minutes intervals, starting from 1.5 V up to 30 V. It is evident that for voltages higher than 5 V the registered changes of acoustic attenuation indicate the massive reorientation of LC molecules. One can also see the fast dynamics of this switching effect, LC molecules change the orientation under the electric field in a few seconds.

However, the magnitude of this effect depends on the intensity of applied electric field and the reorientation of LC molecules registered by acoustic attenuation is not much different for voltages higher than 10 V. The saturation of SAW attenuation represents the situation when most of the LC molecules should be reoriented. Similar dependences of the acoustic attenuation on applied electric field were detected also for other concentrations of magnetic nanoparticles. However, the measured changes increased with the increasing particle concentration. This fact suggests the simultaneous role of dipole moments of magnetic particles. In the pure 6CHBT liquid crystal the effect of applied electric field on acoustic attenuation changes was rather weaker.