26.3: Electro-optical devices from polymer-stabilized liquid crystals with molecular shape polarity

Sang Hwa Kim, Liang-Chy Chien
Chemical Physics Interdisciplinary Program and Liquid Crystal Institute,
Kent State University, Kent, OH, USA
Lachezar Komitov
School of Physics and Engineering physics, Chalmers University of Technology and Gothenburg University, Goteborg, Sweden

Abstract

We present a fast-switching electro-optical device based on flexoelectro-optic effect in short pitch cholesterics oriented in uniform lying helix texture. The device has two operating modes: amplitude and phase modulation mode. The amplitude modulation mode is a fast in-plane switching of the device optic axis that enables to achieve a high percent of modulation of the transmitted light intensity whereas the phase mode gives a continuous change of the refractive index and thus of the phase shift of the transmitted light. By using a small concentration of diacrylate monomer and selecting the illumination conditions we have been able to create a inhomogeneous polymeric network mostly localized at both substrate surfaces and stabilize the two switching modes.

1. Introduction

The cholesteric liquid crystals can adopt a helical structure, in general, Grandjean or fingerprint texture, with helical axis oriented perpendicular or parallel, respectively, to the confining substrates [1]. In the fingerprint texture the helical axis has random in-plane distribution that can be transformed into a uniformly lying helix (ULH) texture, with the helix axis lying everywhere along a unique direction parallel to the substrates [2]. Depending on the pitch and cell gap ratio as well as on the properties of the alignment layer, the helical axis in the ULH texture may be oriented either along or perpendicular to the rubbing direction of the alignment layer deposited on the inner surface of the confining substrates for achieving a uniform alignment of the cholesteric liquid crystal.

A short-pitch cholesteric layer with uniformly laying helix (ULH) texture, i.e. with axis oriented along a unique direction parallel to the device substrates, behaves optically as a uniaxial birefringent crystal plate with optic axis being along the helix axis. Upon rotating the sample between the crossed polarizers, a full extinction of the transmitted light will be achieved when the helix axis coincides with the transmission direction of one of the polarizers. With an applied electrical field across the cholesteric layer, an in-plane deviation of the effective optical axis may occur, an effect described by Patel and Meyer [3]. The effect has been found to be flexoelectric in origin. Furthermore, a relation between the sense of the field-induced deviation of the optic axis, the helix handedness and sign of the average flexoelectric coefficient was found by Komitov et al. [4]. At moderate electric fields, where the dielectric coupling between the liquid crystal molecules and the applied field can be neglected, the field-induced deviation of the optic axis is linear with the field which means that the flexoelectric effect has grey scale capability. For a cell, fulfilling the conditions for $\lambda/2$ optical plate, the field induced in-plane deviation of the sample optic axis of 22.5 degrees (magnitude achieved with some cholesteric materials) will result in a 100% amplitude modulation of the transmitted light intensity. At higher electric fields, when the dielectric coupling between the applied electric field and the liquid crystal bulk becomes strong, the helix could be partially or completely unwound depending on the magnitude of the applied voltage. If the cholesteric liquid crystal posses a positive dielectric anisotropy ($\Delta\varepsilon > 0$), the unwound state will be totally black when looking at the cell placed between crossed polarizers.

The helix unwinding that takes place due to dielectric coupling is a quadratic effect in contrast to the flexoelectro-optic effect which is a polar effect. It should be noted that the helix unwinding by the applied electric field usually destroys irreversibly the ULH texture, i.e., after switching off the field, the ULH texture is never recovered completely, thus resulting in deterioration of the flexoelectro-optic mode of the device. In order to be practical, an electro-optic device based on the flexoelectro-optic effect must withstand a large temperature and field variation and still work functionally. This means, that such a device requires a stable UHL texture which after unwinding by the applied electric field, for instance, will be able to recover completely after switching off the field. The same should be valid for exposing the sample to high temperatures that cause transition to isotropic phase.

There was an attempt to stabilize the ULH texture of a short pitch cholesteric by a polymer network created in the volume of the cholesteric [5]. However, the polymer network created by the method described in [5] produced a substantial residual birefringence that decreased the cell contrast in the unwound state. Moreover, the dense polymer network affects negatively the cell performance as the degree of the light intensity modulation as well as the switching time.

In this work we present an efficient method of forming inhomogeneous polymer distribution using a light-induced localization of polymer network on the surfaces of substrate (Figure 1) for stabilization of the ULH texture of a short pitch cholesteric that substantially improves the device performance.

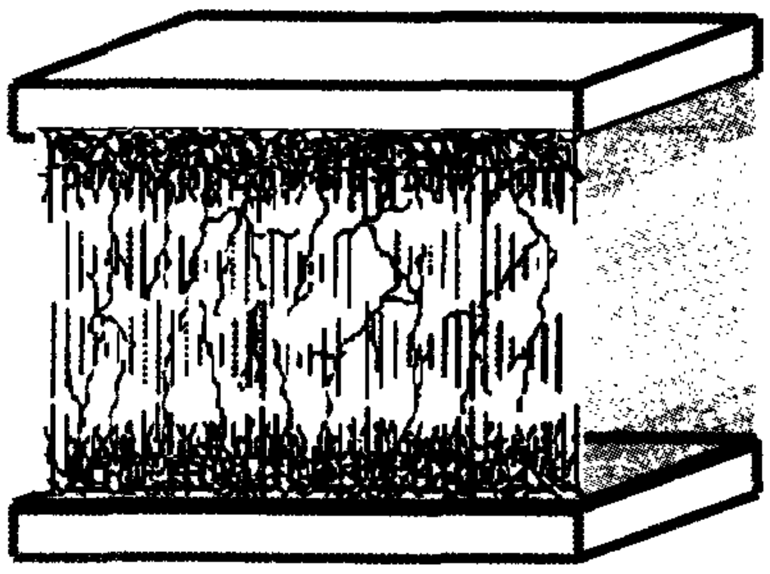

Figure 1. Schematic illustration of a polymer-stabilized ULH (PS-ULH) texture of a short pitch cholesteric liquid crystal with polymer network localized at the surface of substrates.

2. Experimental

The cholesteric material studied in this work was a mixture of the commercial nematic LC MLC 6080 (Merck), chiral dopants CE1, CB15, R-1011 (Merck), reactive nematic monomer RM257 (1,4-bis[3-(acryloyloxy) propyloxy]-2-methyl benzene, Merck), and photoinitiator Irgacure 651 (2,2-dimethoxy-2-phenly acetophenone, Ciba Additives). These materials were homogeneously mixed to have the pitch of the cholesteric mixture about 0.3 μm, i.e. lower than the wavelength of the illuminating light. The short pitch cholesteric liquid crystal material has a positive dielectric anisotropy of 7.2 and it exhibits a pronounced flexoelectric response. The cholesteric liquid crystal is a highly birefringent material, i.e. with $\Delta n \approx 0.2$. EHC (Japan) cells with gap of 2 μm was used in our experiments. It was filled with the cholesteric material into isotropic phase. The alignment layers in this cell (uniaxially rubbed polyimide) provided a uniform planar alignment. The cells was cooled down slowly under an applied *ac* electric field. Due to the positive dielectric anisotropy of the cholesteric material and the uniformly rubbed alignment layer, the cholesteric adopted ULH texture. Once such a texture was obtained, the sample was illuminated in order to create a polymer network that stabilizes the ULH texture. In order to avoid the effect of the residual birefringence arising from the presence of dense anisotropic polymeric network in the bulk of the cholesteric liquid crystal, the illumination of the sample was performed in such way that a non-uniform network was created in the bulk of the cholesteric instead of uniform one, described in [5]. The non-uniform polymer network is characterized by a non-homogeneous distribution of the polymer material across the cell thickness and it has certain advantages compared to the uniform one. The non-uniform polymer network in our device is much denser in the regions in the vicinity to the substrates' surfaces than in the bulk, where the network is very loose. The non-uniform structure of the network was achieved by selecting the illumination conditions. These conditions were chosen in such way that the size of the surface sub-regions, where the network is denser, was smaller than the light wavelength, i.e. less than 0.3 μm, hence the residual birefringence exhibited by the polymeric network in these sub-regions was practically zero, when the helix was unwound. Due to the fact that the polymeric network in the liquid crystal bulk is very loose, this part of the polymeric network also gives negligible residual birefringence either.

3. Results and Discussion

The developed device has two switching modes: *amplitude and phase modulation mode.* The electro-optical device can be switched at the amplitude mode (flexoelectric switching) at a low electric field and in the birefringence mode (dielectric switching) with a higher voltage. Figure 2 illustrates the polarizing optical microscopy textures of the sample switched between 0, 10 and 25 V. At high voltage, the liquid crystal is switched to orient in the direction perpendicular to the substrates. Upon the removal of electric field, the cholesteric liquid crystal returns to the field-off polymer stabilized ULH texture. The electro-optic properties of cholesteric devices in the present study with surface stabilization of the ULH texture of the cholesteric liquid crystal are determined by a set-up consisting of a functional generator, power amplifier, digital scope, a photodiode detector and optical polarizing microscope. Figure 3 shows the plots of digital scope traces of the in-plane flexoelectric switching transmitted light intensity and the switching time is obtained from the digital scope, which shows a turn on (rise) time of 60 μs and a turn off (decay) time of 120 μs at 2 V/μm, square wave, 110 Hz.

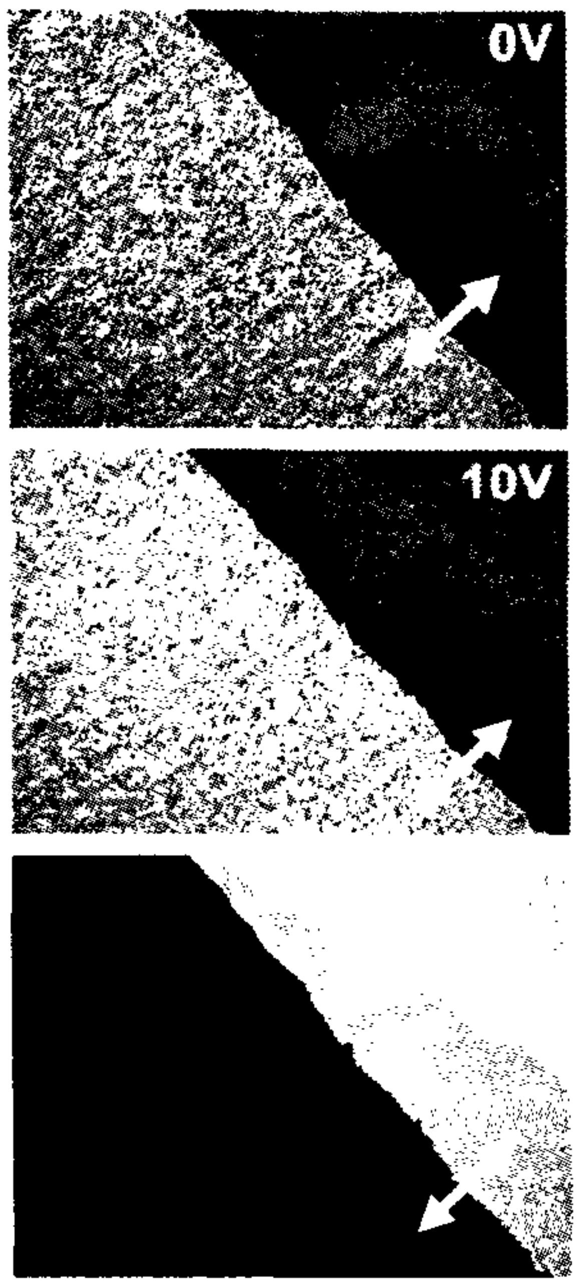

Figure 2. A 2-μm sample cell with inhomogeneous polymer network stabilization of the ULH texture switched between 0, 10, and 25V and viewed between crossed polarizers. At the high applied voltage, the liquid crystal molecules are oriented in the direction perpendicular to the substrates (out-of-plane). As seen in the high voltage (25V) image, there is no any residual birefringence coming from the polymeric network. The arrow represents the rubbing direction.

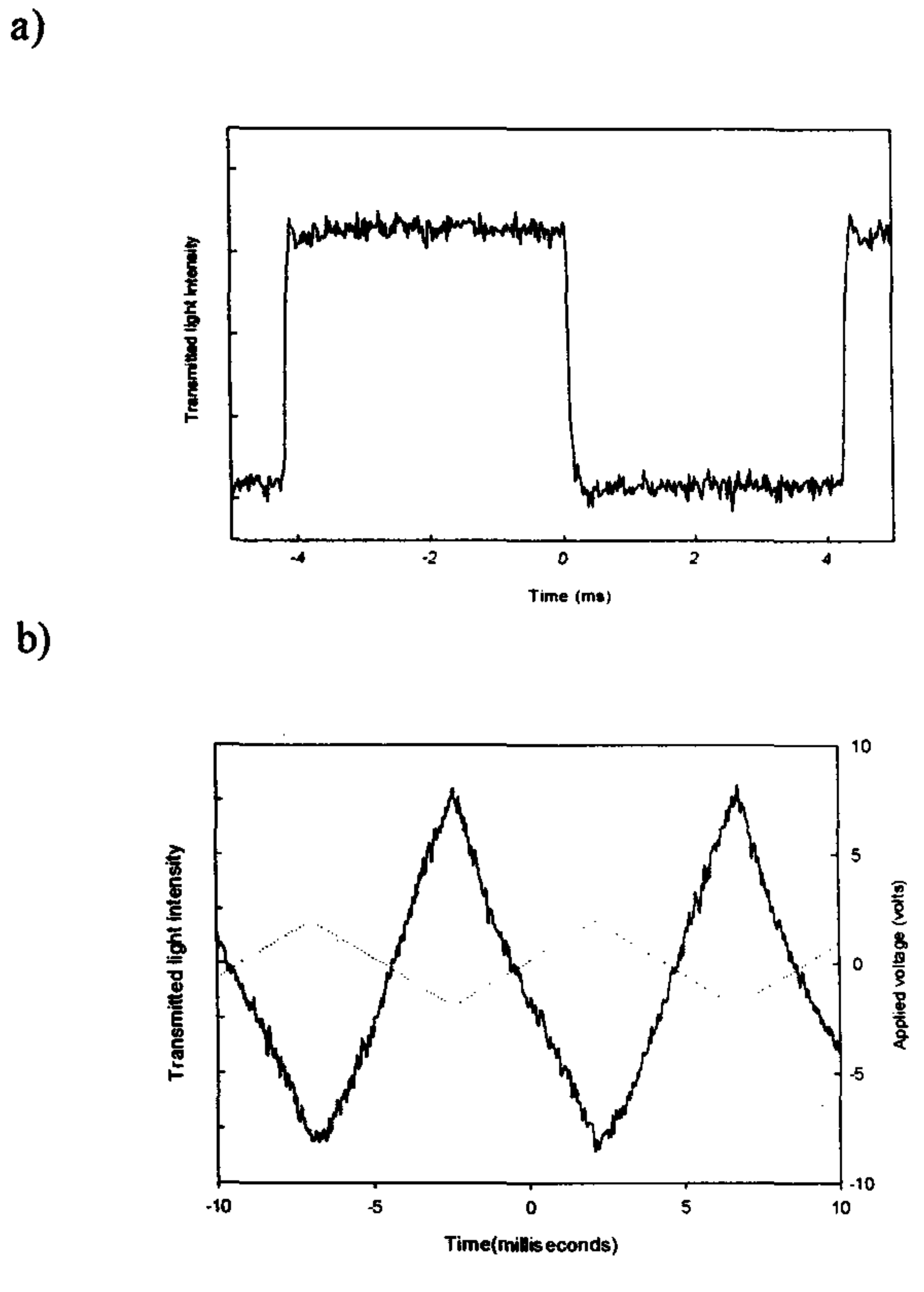

Figure 3. Plots of (a) the flexoelectro-optic response of a 2-μm cell under the applied voltage of 2 V/μm, square wave, 110 Hz, and (b) the symmetrical electro-optic response of the cholesteric device with volume stabilization of the ULH texture versus time for 2-μm cell at 1 V/μm, on application of triangle wave voltage with frequency of 110 Hz.

Figure 4a shows the electro-optic response of a cell driven in amplitude modulation mode (flexoelectric coupling) by a voltage with triangular-wave form. As seen in Fig. 4a curve-1, the response is linear with the applied electric field 2 V/μm. On increasing the magnitude of the electric field to 5 V/μm, the linear character of the response changed and had a mixed character, linear and quadratic since amplitude and phase modulation of the transmitted light took place (Fig. 4a curve-2). Increasing further the applied electric field, the response of the cell change to quadratic (Fig. 4a curve-3, 4) with the field when the complete unwinding of the helix was reached. Now, at higher voltages the device operates in phase modulation mode.

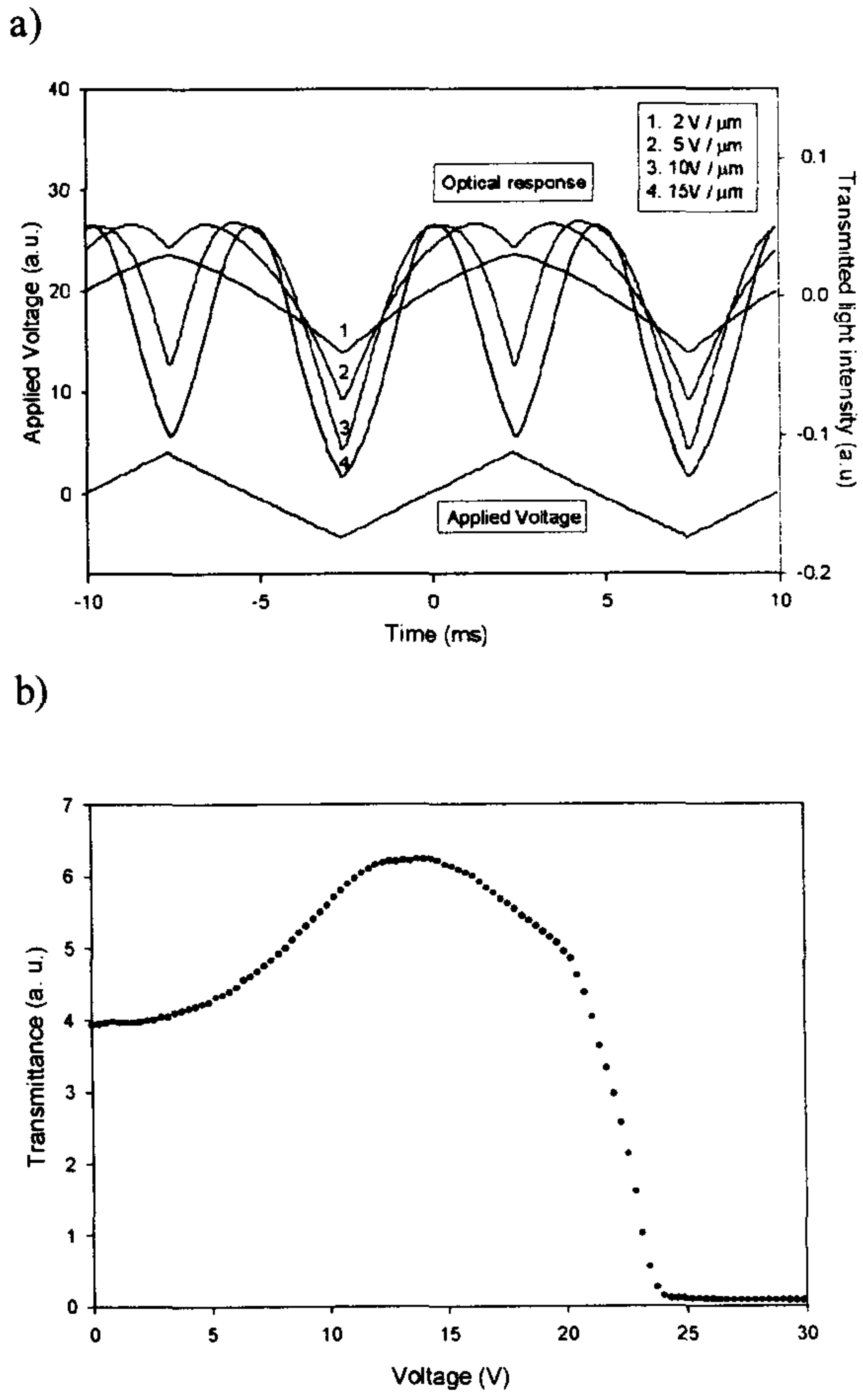

Figure 4. The plots of a 5% polymer sample with 2-μm cell gap (a) the linear and quadratic switching in responding to applied voltage of triangular wave function and (b) voltage-dependent transmittance of the sample switched from 0 to 30V.

The voltage-dependent transmittance of a 2-μm cell sample was investigated and the result is shown in Figure 4b. At V=0, the LC optical axis laid in the plane parallel to the substrates is aligned at an angle in between crossed polarizers. A weak birefringence indicates that the polymer network is anisotropic. As the voltage exceeds the threshold (~5V), the transmittance gradually increases and reaches the maximum at V=13 because of the LC optical axis orientation at 45° with respect to the crossed polarizers. The transmittance gradually decreases as the voltage increased to V=20 indicating that the LC optical axis is switched from a 45° angle toward the other polarizer. The required fields for total unwinding the helix and switching to the homeotropic state is around 24 V.

4. Conclusion

We developed a fast-switching cholesteric liquid crystal electro-optic device that operates in two modes: amplitude and phase. The materials and devices are anticipated to have a wide range of commercial applications in display and non-display areas such as, phase-only spatial light modulators, beam deflectors, and flat panel displays.

This work was supported in part by AFOSR/DAGSI.

5. References

[1] P. de Gennes, "The Physics of Liquid Crystals," Clarendon, Oxford, 1974.

[2] L. Komitov, G. P. Bryan-Brown, E.L.Wood, A. B. J. Smout, *J. Apl. Phys.*, **86**, 3508 (1999).

[3] Conger., S., and Loch, K.D. (eds.). E J. S. Patel and R. B. Meyer, *Phys. Rev. Lett.*, **58**, 1538 (1987).

[4] L. Komitov, S. T. Lagerwall, B. Stebler, and A. Strigazzi, *J. Appl. Phys.*, **76**, 3762 (1994).

[5] P. Rudquist, L. Komitov and S.T. Lagerwall, *Liq. Cryst.*, **24**, 329 (1998)