Voltage Dependence of Hologram Generation Dynamics in Nematic Liquid Crystal Hybrid Panels

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Abstract - **In this paper we present results of the study of dynamics of diffraction efficiency in hybrid liquid crystal panels (HLCP) dependent on applied voltage. In the experiment we used laser to write a hologram by modifying the alignment of liquid crystal molecules. Simultaneously we used a second laser to read the recorded gratings. We proposed the model explaining the dynamics of the gratings formation which is composed of three different following processes related to the charge carriers generation and their mobility in the photo conducting polymer.**

I. INTRODUCTION

Nowadays photonic devices with a potential use for information storage and processing are the subject of increasing interest and development. The photo induced refractive index changes in nematic liquid crystals are very popular among different physical processes enabling the creation of real time holograms. When properly used in optical systems they allow for pattern recognition, moving object extraction, optical filtering, and realization of associative memories. Implementation of such tasks requires sensitive, fast and reversible recording media. The process of hologram formation and erasure generally relies on optical build-up of transient diffraction gratings in a material. [1-2] These gratings understood as a spatial modulation of index of refraction or absorption arise as a result of various non-linear optical processes which are not well described yet. Many parameters require optimization, and with some improvements the hybrid liquid crystal panels (HLCP) could become a very efficient storage medium for large amounts of data in small areas.

The purpose of the research reported in this contribution was to investigate the dynamics of diffraction efficiency in HLCP dependent on applied voltage.

II. EXPERIMENT

A. Sample

The investigated liquid crystal panel was made by sandwiching nematic liquid crystal between two ITO (Indium Tin Oxide) glass plates onto which thin layers of photo-conducting polymer were spin-coated. Scheme of the sandwich-type HLCP is shown in Fig.1.

For sample preparation we used poly(N-vinylocarbazole) sensitized on visible light spectra by doping the trinitrofluorenone molecules (PVK + TNF).

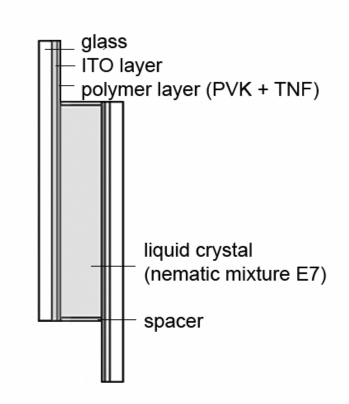

Figure 1. Hybrid nematic liquid crystal panel (HLCP)

The thickness of this layer was about 100 nm. The multicomponent nematic liquid crystal mixture E7 (Merck, Darmstadt, Germany) was used as the “optically active” medium.

The distance between ITO plates was set by 10 μm spacers. Surfaces of the photo-conducting thin layers were uniaxially brushed to preliminary direct the molecules of the liquid crystal without the influence of an applied voltage.

B. Experimental set-up

All measurements were done in a typical degenerated two wave mixing experiment set-up which is schematically shown in Fig. 2 [3].

Nd:YAG laser “L1”, which operates on wavelength λ = 532 nm was used to write a hologram by modifying the alignment of liquid crystal molecules. The writing laser beam was firstly partially attenuated by the grey filter “F” and then was divided into two beams “Iw(1)” and “Iw(2)” by the beam splitter “BS”. The intensities of these beams were not equal so the gradient filter “GF” was used to compensate for the difference.

The mirror “M” was used to direct beam “Iw(2)” onto sample “HLCP” to allow interference with beam “Iw(1)” within the sample volume. Interfering beams caused modulation of the refractive index Δn.

A second laser He-Ne “L2”, which operates on wavelength λ = 632.8 nm was used to read the stored image.

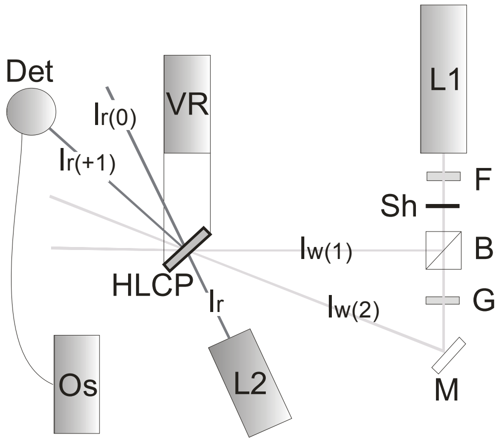

Figure 2. Experimental set-up for degenerated two wave mixing measurements. L1 – Nd:YAG laser, L2 – He-Ne laser, F – grey filter, GF – gradient filter, Sh – shutter, BS – beam splitter, M – mirror, S – sample, VR – voltage regulator, Det – detector, Os - oscilloscope.

Power of the first order diffraction beam “Ir(+1)” was measured by silicon detector “Det” coupled with digital oscilloscope “Os”.

Power Supply "VR" of DC voltage connected to the sample was regulated within the range of 0-50V. Diffraction efficiency was measured in dependency of applied to the HLCP voltage. All the following parameters were fixed. The reading angle (angle between normal to the sample surface and reading beam) was set to β = 12º, the writing angle (the angle between writing beams Iw(1) and Iw(2)) was set to 2θ= 4º and the tilt angle (the angle between bisector of writing beams and normal to the sample surface) was α = 0º. The power of writing beams were Iw(1) = Iw(2) = 19mW and the power of reading beam was Ir = 15mW.

III. Theory

Experimentally diffraction efficiency η is calculated from the measured intensity of light in a certain diffraction order. This figure is determined as the ratio of intensity of diffracted light in a first diffraction order Ir(+1) to the intensity of incident light Ir.

$$\eta = \frac{Ir(+1)}{Ir} \tag{1}$$

Theoretically diffraction efficiency η (for thin diffraction gratings) is determined by using the Raman-Nath approximation. This approximation can be used to link diffraction efficiency with the alteration of the composite refractive index by Δn* Bessel functions J_1 [4,5]

$$\eta = \left|J_1(\phi)\right|^2 \tag{2}$$

$$\phi = \frac{2\pi\Delta n^* d}{\lambda} \tag{3}$$

$$\Delta n^* = \Delta n + i\frac{\Delta\kappa\lambda}{4\pi} \tag{4}$$

where d – the thickness of the liquid crystal panel
λ – wavelength of the writing laser
Δκ –modulation of absorption coefficient
Δn – modulation of refractive index

If absorption of the refractive material is insignificantly small, the Bessel function parameter for thin diffraction gratings can be written in the form of

$$\phi = \frac{2\pi\Delta nd}{\lambda} \tag{5}$$

For the writing laser wavelength of light of λ = 632.8 nm and the thickness of the liquid crystal panel, d = 10µm parameter value 2πd/λ = 99.1.

The sinusoidal light modulation caused by interfering light in the volume of sample generates charge carriers in PVK:TNF layers. Number of generated carriers is proportional to the intensity of incident light, so generation is strongest in the places where constructive interference occurs and none where destructive interference occurs.

When the sample is illuminated, DC voltage is applied and when it’s value is over Freedericksz potential, the generation of the charges and their drift into the photo-conducting layers provides changes to the local electric field, which results in liquid crystal molecules reorientation and then spatial refractive index modulation in the sample.

The charge generation and transport in HLCP can be divided into three different following processes (Δn_1, Δn_2, Δn_3). These three processes are characterized by the following parameters:

- amplitudes determining the quantitative contribution of each of the processes. (n_{1M}, n_{2M}, n_{3M})
- stable in time angles between different diffraction gratings ($\varphi_{1/2}$, $\varphi_{1/3}$, $\varphi_{2/3}$) determining their relative position
- time constants (τ_1, τ_2, τ_3) determining the rate of exponential growth of gratings writing
- time constants of erasing functions (τ_{1e}, τ_{2e}, τ_{3e})

Basing on the preceding assumptions we developed the following mathematical model for description of modulation of the refractive index during diffraction gratings writing process which is based on gratings coupling [6].

$$\Delta n = [\Delta n_1^2+\Delta n_2^2+\Delta n_3^2 + 2\cdot\Delta n_1\cdot\Delta n_2\cdot\cos(\varphi_{1/2}) + 2\cdot\Delta n_1\cdot\Delta n_3\cdot\cos(\varphi_{1/3}) + 2\cdot\Delta n_2\cdot\Delta n_3\cdot\cos(\varphi_{2/3})]^{1/2} \tag{6}$$

$$\Delta n_i = n_{iM}(1-e^{-t/\tau i})\cdot e^{-t/\tau ie} \quad , i = 1, 2, 3 \tag{7}$$

IV. Results and Discussion

Temporal evolution of diffraction efficiency was measured for different values of applied to the HLCP voltage. The experimental data indicate that diffraction efficiency generally increases with increasing voltage. This is due to the fact that the number of generated charge carriers responsible for the efficiency of the process of hologram writing depends on applied to the HLCP voltage. Temporal evolution of diffraction efficiency for different values of applied to the HLCP voltage is shown in Fig. 3.

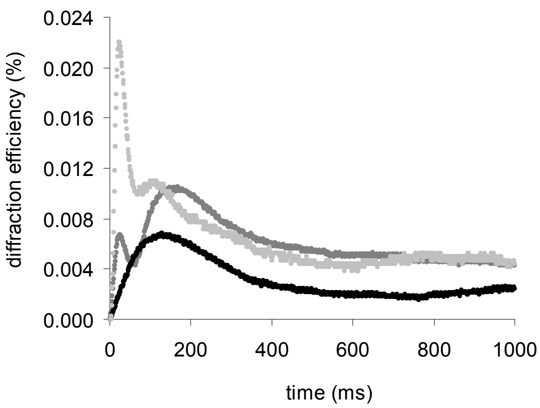

Figure 3. Temporal evolution of diffraction efficiency for different values of applied to the HLCP voltage.
Black curve – 32V, dark grey curve – 40V, light grey curve – 50V.

Diffraction efficiency depends on the modulation of the effective refractive index, which described by formula (6) consists of three different following processes (Δn_1, Δn_2, Δn_3). For the processes of diffraction gratings formation most of the parameters characterizing those three processes change when applied to the HLCP voltage changes as shown in Table 1.

The first process which occurs in first few milliseconds after irradiation of the sample can be explained as generation of electrons and holes in the bright regions of both PVK:TNF layers, diffusion of holes into the dark regions of polymer layers on anode side (redistribution of holes near the border between PVK:TNF layer and liquid crystal at anode side). Time constant of the first diffraction grating (τ_1 = 20ms) remains constant, so it can be concluded that it is independent of voltage applied to the HLCP. Amplitude of this process (n_{1M}) increases with increasing voltage and time constant of the erasing function (τ_{1e}) decreases.

The next process occurs within several tens of milliseconds and is connected with the depletion of faster holes at cathode side and charge transfer in external electric field. Time constant of this process (τ_2) changes linearly with changing inverse voltage and time constant of the erasing function (τ_{2e}) has infinite value so it can be assumed that it has no effect on the process of writing of the second grating.

The last process takes a few hundred milliseconds. Charge is transferred from side holes located on anode to the molecules of liquid crystal which results in the flow of the cations through the sample volume and their arrival to PVK:TNF layer at the cathode side. This process leads to neutralization of electrons present in the cathode. Time constant of this process (τ_3) also changes linearly with changing inverse voltage and time constant of the erasing function (τ_{3e}) has infinite value similarly to the second process so it can be assumed that it has no effect on the process of writing of the third grating.

TABLE I
THE SET OF APPROXIMATION PARAMETERS FOR THE SERIES OF EXPERIMENTAL CURVES OF WRITING DYNAMICS OF THE HOLOGRAM CALCULATED USING THE EQUATION (6)

U [V]	τ_1 [ms]	τ_2 [ms]	τ_3 [ms]	n_{1M} [10^{-5}]	n_{2M} [10^{-5}]	n_{3M} [10^{-5}]
32	20.0	56.0	580.0	0.0	26.0	37.0
36	20.0	47.0	554.0	70.8	104.9	98.7
40	20.0	39.5	534.0	97.2	125.9	113.0
44	20.0	33.5	517.0	154.6	182.9	170.7
48	20.0	28.0	504.0	237.1	259.5	264.4
50	20.0	25.5	498.0	294.8	306.7	288.0

U [V]	τ_{1e} [ms]	τ_{2e} [ms]	τ_{3e} [ms]	$\varphi_{1/2}$ [rad]	$\varphi_{1/3}$ [rad]	$\varphi_{2/3}$ [rad]
32	1300	∞	∞	2.81	0.00	2.81
36	1050	∞	∞	3.01	-0.01	3.02
40	858	∞	∞	3.00	-0.05	3.05
44	700	∞	∞	3.04	-0.06	3.10
48	580	∞	∞	3.05	-0.08	3.13
50	520	∞	∞	3.06	-0.09	3.15

Approximated curves very accurately coincide with the experimental data obtained for various experimental conditions. In Fig.4. experimental data of dynamics of diffraction efficiency and estimated values for the process of hologram writing for applied to the HLCP voltage U = 40V are shown.

After shutter release a rapid increase in the diffraction efficiency was observed. After 25 ms it reached the local maximum value of 0.0067%, then started to decrease and reached a minimum value of 0.0043% in the 55 ms of experiment, then rise again to the maximum value of 0.0104% in the 165 ms of experiment and decreased slowly to the value of 0.0044% and stabilized after 1000 ms from the start of the experiment.

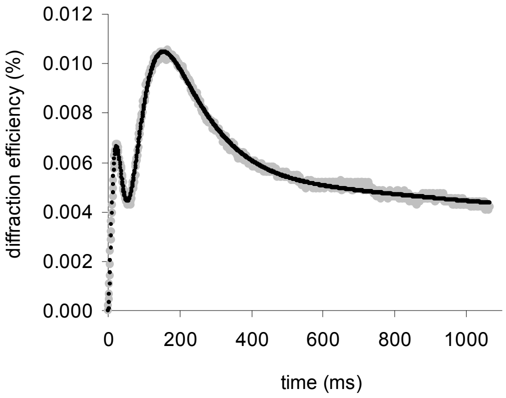

Figure 4. Typical time dependency of diffraction efficiency for HLCP.
Gray points – experimental data, black points – estimated values (parameters of estimation can be found in Table 1.)

V. CONCLUSION

In conclusion, we have demonstrated the results of the comparison between experimental and estimated data.

The presented mathematical model which takes into account the existence of charge carriers (holes and electrons) and their mobility in the photo conducting polymer fairly well describes the three-step process occurring inside the HLCP during the hologram writing.

The calculated parameters characterizing proposed mathematical model show that the dynamics of the hologram writing is linked to the generation and transport of charge carriers (diffusion and drift) in the external electric field.

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