Electrically Controlled Dynamics of Energy Transfer in Pure Nematic Liquid Crystals

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Abstract – The photorefractive effect in homeotropically aligned layer of pure nematic liquid crystal 5CB is investigated by the dynamic holographic technique. It is found the voltage controlled energy transfer between two interacting waves. The efficiency of the energy transfer, its direction and time characteristics are investigated. A surface charge-dependent photorefractive effect as well as a bulk effect determined by the molecular interaction are discussed as two complementary mechanisms of the dynamical grating recording.

I. INTRODUCTION

Modern researches in the field of optical information processing are directed to develop new optical technologies based on dissipative nonlinearities in different photonic media for application in digital optics. The efforts are directed to develop new generation of nonlinear optical devices for transformation of optical information, which involves (but not restricted to) light interferometers, optical logic, optical modulators, and optical amplifiers [1]. All-optical switching allows one to significantly increase the bandwidth of optical communication networks. The dynamic holography with two input interacting beams represents one of the technologies that may implement the all-optical switching of the beams. A remarkable property of the dynamic holography is the energy transfer between interacting beams, which is realized when the dynamical grating is shifted relative to the illuminating intensity pattern. That can be used for controlling and amplification of the light beams during their interaction, which have significantly different intensities.

Liquid crystals (LCs) occupy an important niche in nonlinear optics due to their unique physical, particularly, optical properties [2]. LCs possess extraordinarily large optical nonlinearities. To date, a lot of nonlinear optical phenomena have been observed in LCs in a very broad spectral range. A new wave of interest in nonlinear optics of LCs and LC based composites observed in last years is caused by unique photorefractive effect that can be managed electrically, and its potential applications in the signal processing, propagation and control of solitons. In this paper we are focused on the dynamics of the photorefractive processes in cells filled with pure LC material in dependence on applied voltage. Our interest is to study the properties of the energy transfer in these cells during the self-diffraction of waves, to find out their possible applications for nonlinear photonic devices.

II. MULTI-ORDER SELF-DIFFRACTION IN PURE HOMEOTROPIC 5CB CELLS

To eliminate effects caused by impurities introduced from outside, pure LC 5CB and bare substrates were used in our samples. The cell with a thickness of 20 μm was assembled using two equal ITO/glass substrates. The 5CB molecules in the cell took homeotropic alignment.

The experimental set-up for the two-wave mixing with pure LC cells is shown in Fig. 1. A Nd^{3+} continuous laser is used with output a total power of 50 mW. The intensity of every input recording beam is 0.5 W/cm^2. The period of the recorded gratings was 30 μm. After applying dc voltage, we defined the grating recording by observing two additional diffraction orders (+1 and −1) aside from main orders of the recording beams (+0 and −0), or even more diffraction orders. Our designation of the orders is shown in Fig. 1. The maximal diffraction efficiency is observed when a cell is rotated by the angle $\delta=45^0$ relative to the bisector of the convergence angle of two input beams [3-5].

In our experiments we were concentrated on the self-diffraction process, accompanied by the energy transfer between the interacting waves. This feature indicates that the nonlinear response is nonlocal, i.e. there exists the space shift between the interference pattern (the light grating) and the photo-induced refractive index grating. The changes in intensities of +1 and −1 diffraction orders are studied by switching the applied voltage between different levels. The typical kinetic curves are shown in Fig. 2, where the applied voltage is switched from 1.5 V to 3 V. Considerably higher intensity of +1 order comparing with −1 order indicates the energy transfer to the orders marked by positive numbers (see Fig. 1). The transient process usually takes tens of seconds after switching the voltage.

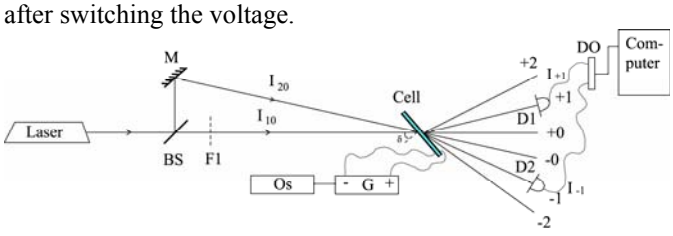

Fig. 1. The experimental set-up of the multi-order self-diffraction during two-wave mixing on LC cells. BS – beam splitter, M – mirror, F1 – filter, G – generator of dc voltage, Os – oscilloscope, D1, D2 – photo-diodes, DO – digital oscillograph.

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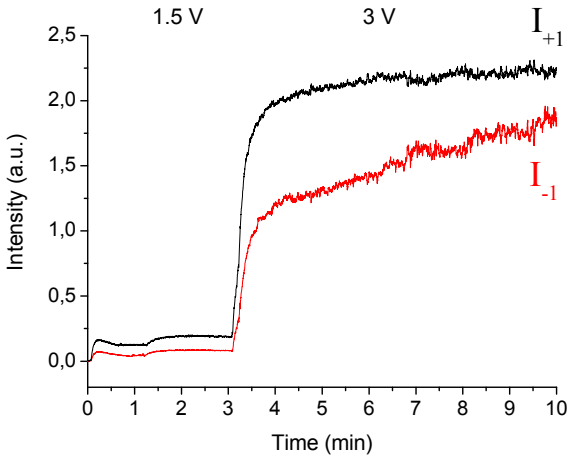

Fig. 2. The time-behavior of the intensity in the +1 diffraction order (I_{+1}) and in the –1 diffraction order (I_{-1}) with switching the voltage from 1.5 V to 3 V. The input intensity ratio is equal: I_{10}:I_{20} = 1 : 1. The sample was held under applied voltage 4 V during 10 min before switching on the light.

The features of multi-order diffraction in pure 5CB cells can be explained in the framework of surface photorefractive effect. Periodic charge distribution on the ITO electrode is given by the fringe interference pattern of the illuminating light. It was assumed that a desorption of charges from the surface into the volume of LC occurs in the bright parts of the light fringes [4, 5]. As the result, the periodic distribution of the charge appears on the surface that gives rise to the periodic modulation of the molecular orientation [6]. The spatial modulation of the director, which is started on the surface, spreads on the volume of the cell. Thereby the grating of the refractive index is formed due to modulation of the molecular orientation.

Surface photorefractive effect in pure 5CB has some peculiarities (see [4, 5]). In such cells, the voltage applied before illuminating by a laser beam leads to increasing the diffraction efficiency. Moreover, the recorded gratings can remain on the cells up to several days. The publications note that the direction of the energy transfer depends on the rotation angle of the cell (+δ or –δ) and the direction of the applied voltage (+U or –U).

III. FAST INTENSITY FLASH

In addition to slow dynamics of the grating recording we have observed the fast flash of the intensities in the diffraction orders with smooth increasing/decreasing of the voltage. Such flash occurs when a stable grating is formed under a certain dc voltage, but after some changes in the voltage. This flash can be accompanied by the change in the direction of the energy transfer between diffraction orders. Some typical curves are shown in Fig. 3, where change in the direction of energy transfer is happened in the second flash. The kinetic process takes up to ~0.5 sec. After the fast burst is finished, a conventional process of the recording of a stable grating starts. Most probably the change of the ordered spatial

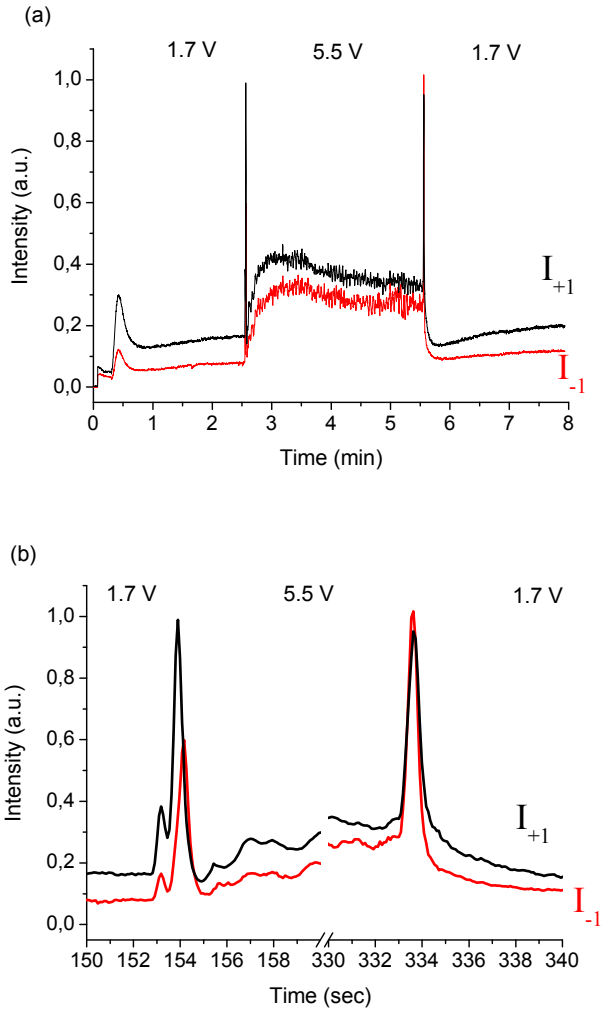

Fig. 3. (a) Fast flash with increasing the voltage at the time t=2.5 min and decreasing the voltage at the time t=5.5 min. (b) More precise kinetics of the flash. One can see the change in the direction of the energy transfer during the flash. I_{10}:I_{20} = 1 : 1

structure of the molecules takes place during changing the voltage. The modeling of this process in pure LC cells is under investigation.

IV. CONTROL OF ENERGY TRANSFER DEPENDING ON THE INTENSITY RATIO OF INPUT BEAMS

As mentioned above, the grating recording in pure LC has been explained by the photorefractive effect induced by charge redistribution on a surface. In such a case, the diffraction efficiency is maximal, when two interacting waves will have equal input intensities. This is because the interference pattern will have the highest contrast on the surface, which modulates the charge distribution.

We studied the energy transfer in dependence of input intensity ratio. The filter was used to change the intensity of input waves. In these experiments, a sample was first under the voltage U=4 V during 10 min, then the grating was recorded during 10 min at the same voltage, and after that the

voltage was decreased to 1.5 V at which a new stable grating was formed. This procedure ensured the repeatability of the diffraction efficiency of the last grating.

Figs. 4 and 5 show ratio of the intensities in the first diffraction orders I_{+1}/I_{-1} for different input intensity ratios for the grating, which was recorded at the voltage 1.5 V. The curve in Fig.5 was calculated from the data of Fig.4. One can see that the energy transfer is increased almost in 2 times for the intensity ratio $I_{10}:I_{20}$=0.9:1 comparing with a case of equal input intensities. It was recently shown that the self-diffraction of waves in nonlocal nonlinear medium can be described by a complex Ginzburg-Landau equation [7]. This equation gives soliton-type solutions, i.e. stable localized structures, which can be either spatial, or temporary, or both spatial-temporary ones [8]. In the case of the wave self-diffraction, the localized profile of the light intensity is formed in the volume of a nonlinear medium (along the direction of the thickness of a cell) as a result of the energy transfer between the interacting waves [9]. The maximum intensity will be achieved in the spatial point in the bulk, where the intensities of two interacting waves become equal due to the energy transfer. Then the diffraction efficiency should be increased when the input waves have not equal intensities [10]. Our experiments are directed to verify this effect for pure LC cells. Indeed, this process should occur in a LC medium because of all the necessary conditions are satisfied; namely the nonlinear mechanism of the grating recording lies in reorientation of the molecules in a bulk of a cell, the nonlinear coefficient is very high for the orientation mechanism in LC, and the grating is shifted relative to the light interference pattern due to the mechanism.

V. Conclusion

Our experiments show that the self-diffraction of waves in pure LC cells exhibits many interesting features. They include the extended range of diffraction efficiency, controlling of the energy transfer between diffraction orders, variation of the time kinetic constants of the grating recording, all of which can be controlled by the applied electric voltage. Intrinsic nonlinear mechanisms represent an independent interest in fundamental research that includes surface charge-induced reorientation of the director, turning into the reorientation of the molecules in the bulk which depends on the light intensity at every local spacial point. Besides, the obtained results give additional options for guiding and switching the laser beams, where the control parameters are not only a value of the electric voltage, but also intensity ratio between input interacting waves.

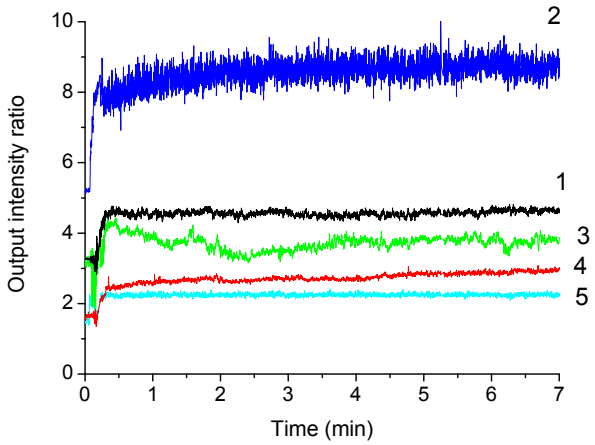

Fig. 4. The kinetics of the intensity ratio in the first diffraction orders I_{+1}/I_{-1} in dependence of input intensity ratio $I_{10}:I_{20}$: 1 – 1:1; 2 – 0.9:1; 3 – 0.8:1; 4 – 1:0.85; 5 – 0.6:1.

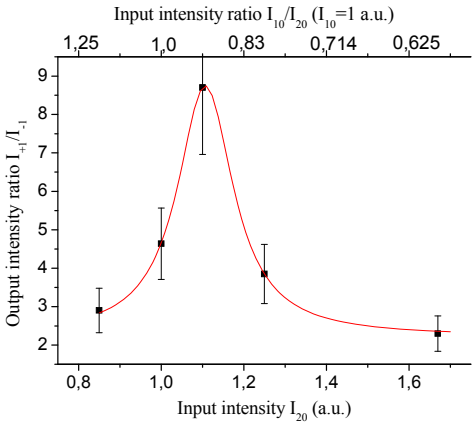

Fig. 5. The energy transfer in the first diffraction orders I_{+1}/I_{-1} in dependence of input intensity ratio $I_{10}:I_{20}$ (we assume I_{10}=1 a.u.).

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