Dynamic grating recording in liquid crystal light valve with semiconductor substrate

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ABSTRACT

Liquid crystal light valve with GaAs substrate operating in the transmission mode in the infrared is studied. The nonlinear phase shift of the transmitted light wave is measured as a function of applied voltage. The dynamic grating recording is achieved. A fourfold amplification of the weak signal beam is reached. The gain is increased by means of proper tilting of the cell that increases an effective pretilt of the liquid crystal molecules. The amplitude of the refractive index modulation and nonlinear coupling constant are estimated from the experimental results.

Keywords: liquid crystal light valve, dynamic gratings, dynamic holography, liquid crystals, spatial light modulators, infrared

1. INTRODUCTION

Many modern applications involving dynamic holography require materials compatible with telecommunication components, which operate in the infrared spectral range. Traditional photorefractive wide-bandgap ferroelectrics with large coupling constants in the visible spectral region generally are not sensitive in the infrared at all. There are only few that are sensitive like rhodium doped barium titanate[1] and tin hypothiodiphosphate[2], but these crystals are slow. Photorefractive semiconductors like gallium arsenide[3,4], indium phosphate[4], and cadmium telluride[5] are sensitive in the infrared, but they have relatively small electro-optic coefficients. In addition, the coupling constants are always reduced in the infrared as compared to the visible range of spectrum because they are inversely proportional to the wavelength. Therefore achieving a large coupling constant, which ensures large amplification of the weak beam, is not an easy task in the infrared.

One possible way to achieve the aim is to combine in one device liquid crystal (LC) with huge refractive index modulation and semiconductor sensitive in the infrared. In such hybrid devices a driving force is created in photosensitive substrate. This driving force affects LC and creates large refractive index modulation in it. Two main types of such hybrids may be distinguished. In the photorefractive–LC hybrids[6] the space charge field is created in the substrate under nonhomogeneous illumination. This space-charge field affects the spatial alignment of the LC molecules via flexoelectric effect. As a result the refractive index becomes spatially modulated in the LC. The hybrids of a second type are liquid crystal light valves[7] (LCLV), in which the driving force is a spatial modulation of the conductivity in substrate. In the present work we are focusing on LCLV because such devices ensure larger amplification of a weak signal light wave.

LCLVs are studied as spatial light modulators since 1970s. The first device operating in the transmission mode was demonstrated using photorefractive $B_{12}SiO_{20}$ substrate[7]. LCLVs are actively studied in the visible range of spectrum. Many spectacular results were reported in the field of light beam amplification[8], slow and fast light[9], adaptive interferometers[10], etc. Nonlinear lens was demonstrated in the infrared for LCLV with gallium arsenide substrate[11] and the recording of dynamic holograms was achieved[12,13] in this spectral range, too.

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In this work we study LCLV with GaAs substrate, which allows recording of dynamic holograms in the infrared. The interaction of the recording waves is studied at the wavelength λ = 1.064 μm for different grating spacings, intensities, and intensity ratios of the recording beams. The nonlinear optical properties of the device are estimated from experimental data.

2. LCLV DESIGN AND EXPERIMENTAL SET-UP

The general design of the LCLV is shown schematically in Fig. 1a. The input window is made of the photoconductive material PhC. The output window is a glass plate. Two transparent indium tin oxide (ITO) electrodes are deposited in such a way that the voltage is applied across the substrate and LC. When the photoconductive substrate is illuminated by the interference pattern created by two intersecting light waves, as it is shown in Fig. 1b, the resistance of the substrate becomes spatially modulated. As a result the voltage across LC becomes spatially modulated. LC molecules are reoriented correspondently and in such a way the refractive index grating is created in the LC. It is important to understand that the conductivity grating in the substrate is local and it is dynamic. The index grating in LC is pinned to the conductivity grating.

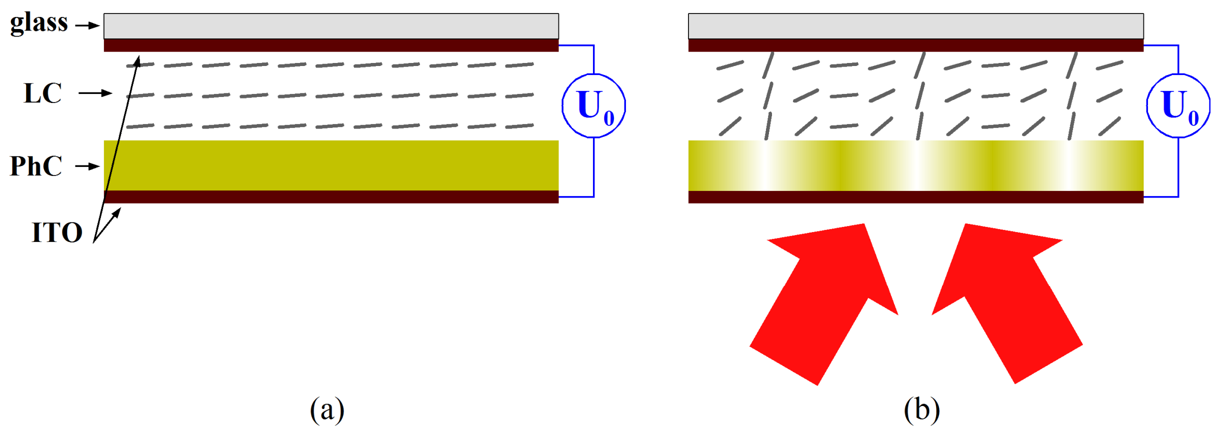


Figure 1. Schematic representations of the LCLV: (a) – in the dark, (b) – during dynamic hologram recording.

An optically finished 3 mm thick 8×15 mm^2 GaAs substrate serves as an input window in our LCLV cell. It is made of nominally undoped semiinsulating GaAs single-crystal with dark resistivity on the order of 5×10^8 Ohm×cm. The absorption constant of the substrate is about α = 1 cm^{-1}. The cell is filled with BL006 (Merck) LC. Mechanically rubbed polyimide alignment layer deposited on the inside face of the semiconductor substrate and on the glass face coated by ITO ensures planar orientation of the LC. The LC layer thickness d = 10 μm is set by spherical glass spacers. Sinusoidal ac voltage is applied to the ITO electrodes.

The experimental set-up for study of the wave mixing in the LCLV is shown schematically in Fig. 2. The single-mode single-frequency diode-pumped Nd^{3+}:YAG laser emitting at λ = 1.064 mm is used as a light source. The output laser radiation polarized in the plane of incidence is expanded and divided by a variable beam splitter BS into two beams I_s and I_p with typical intensity ratio $\beta = I_p(z{=}0)/I_s(z{=}0) \approx 80$. Both beams have a Gaussian intensity distribution with about 20 mm full-width at half maximum on the cell input face. The diaphragm with diameter 5 mm placed on the input cell face cuts the central part of the recording beams ensuring spatial homogeneity of the light intensity within ± 4%. The total light power is about 400 mW. Neutral density filters are used to change the light intensity.

Two beams I_s and I_p are crossed in the GaAs window as shown in Fig. 2 recording index grating in the LC. The temporal dynamics of the intensity of the transmitted signal beam is studied for different experimental conditions. To separate the transmitted signal beam from the pump its intensity is measured behind 0.5 mm diameter diaphragm placed at the focal plane of a lens with 25 cm focal length. The LCLV is placed on a rotation stage, which allows rotation of the cell in the plane of incidence by angle θ around the vertical axis.

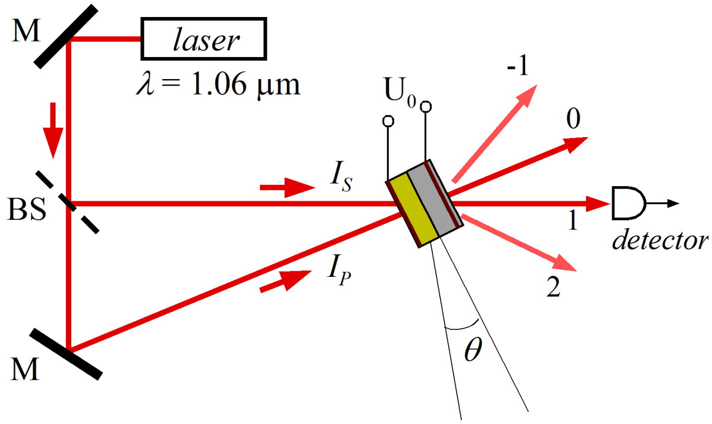


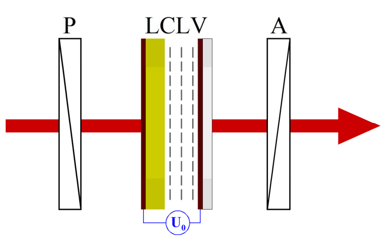
Figure 2. Experimental set-up for the study of wave mixing in the GaAs-based LCLV.

3. EXPERIMENTAL RESULTS AND DISCUSSION

First, to check that the cell exhibits nonlinear optical properties, the nonlinear phase shift induced for the transmitted light wave is studied in a homogenously illuminated cell. For this purpose the cell is placed between crossed polarizer and analyzer as it is shown in Fig. 3a. The LC director is aligned at 45° with respect to the polarization of the input wave. The transmission of such system is determined by simple relation

$$T \propto \sin^2 \frac{\Delta\varphi}{2}, \qquad (1)$$

where $\Delta\varphi$ is the phase shift introduced into the transmitted wave. The phase shift calculated from experimentally measured transmittance as a function of the amplitude of applied voltage is shown in Fig. 3b. This dependence is very similar to that reported previously also for GaAs-based LCLV[11]. The phase shift $|3.5\pi|$ is estimated for 8 V applied field. The self-defocusing of the beam is observed behind the cell for a beam with Gaussian intensity profile. Therefore we conclude that the nonlinear phase shift is negative, as it is expected from the values of ordinary and extraordinary refractive indexes. This conclusion is confirmed also in other works on GaAs-based LCLV[11,13].



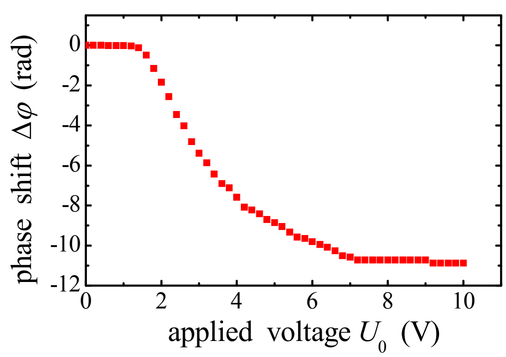


Figure 3. (a) – light wave propagation for measurements of the induced phase shift; (b) – phase shift as a function of the amplitude of applied sinusoidal voltage.

It is well known that the local index grating, i.e., the grating coinciding or shifted by π with respect to the interference pattern, cannot give rise to amplification of the weak beam in the steady state[14]. Obviously the conductivity grating recorded in the photoconductive substrate is local. Therefore amplification of the weak beam is not expected in the steady state. However, the grating recorded in the LCLV is not a usual local dynamic grating. There is no fringe bending, which appears in the local grating due to nonlinear phase coupling. The refractive index grating in the LC is rigidly attached to the conductivity grating created in the substrate. Thus the grating in LC is fixed thin local grating with respect to the recording interference pattern. Such a grating may give rise to the amplification of the weak beam due to the diffraction of light from the strong pump beam in the direction of the weak signal. Understanding of this particular property of the LCLV allowed light beam amplification in the visible spectral range[8].

To demonstrate signal beam gain with our LCLV the temporal envelop of the transmitted weak signal beam is studied. The grating with grating spacing Λ = 440 μm is recorded by beams with total light intensity I = 30 mW/cm^2 and intensity ratio β = 80. The sinusoidal voltage with amplitude U_0 = 2.6 V and frequency f = 20 kHz is applied across the cell. The pump beam continuously illuminates the LCLV to keep electrical properties of the cell in the steady state. At time t = 0 the signal beam is unblocked. The temporal variation of the normalized intensity of the signal beam behind the cell $I_s(z=d, t)/I_s(z=0, t)$ is shown in Fig. 4. The transmitted intensity increases with time and fourfold gain $G = I_s(z=d)/I_s(z=0)$ = 4 is reached in the steady state. This gain is smaller than the gain G = 10 achieved with BSO-based LCLV in the visible spectral range[11], but larger than the largest gain $G = \exp(Gd)$ = 2.7[12] ever reported for a photorefractive semiconductor at λ = 1.064 μm without high voltage applied to the crystal.

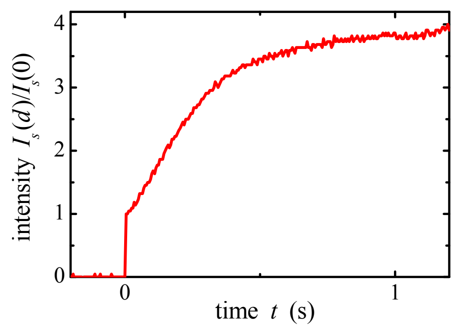


Figure 4. Temporal envelop of the transmitted signal beam intensity; the pump beam continuously illuminates the LCLV, the signal beam is unblocked at t = 0.

The grating in LC is thin and operates in the Raman-Nath regime with the diffraction efficiency in the m-th order defined as

$$\eta_m = J_m^2\left(\frac{\pi\,\Delta n\, d}{\lambda}\right), \tag{2}$$

where J_m is the Bessel function of the m-th order and Δn is the amplitude of refractive index modulation in the LC layer. For large beam ratio $\beta >> 1$ the diffraction efficiency is small $\eta << 1$ and only ± 1 orders of diffraction are important. The last fact is confirmed in the experiment – only ± 1 orders of diffraction are observed behind the LCLV. Therefore the diffraction efficiency is simplified

$$\eta = \left(\frac{\pi\,\Delta n\, d}{\lambda}\right)^2. \tag{3}$$

The intensity of the signal beam behind the cell may be written now taken into account the component diffracted from the pump:

$$I_s(d) = I_s(0) + \eta I_p(0) = I_s(0) + \left(\frac{\pi\,\Delta n\, d}{\lambda}\right)^2 I_p(0). \tag{4}$$

The LCLV may be considered as a device exhibiting Kerr-like nonlinearity[8,15] with nonlinear coefficient $n_2 = \partial n/\partial I$ because the conductivity of the substrate (and therefore the voltage across LC and the refractive index modulation) is linearly proportional to intensity in a certain small intensity range. In this case the amplitude of refractive index modulation is defined as $\Delta n = n_2 m I = 2n_2\sqrt{I_s I_p}$, where I is the total average light intensity and m is the contrast of the interference pattern. Thus, the gain of the signal beam may be written[8,15]

$$G = \frac{I_s(d)}{I_s(0)} = 1 + \left(\frac{2\pi\, n_2\, I\, d}{\lambda}\right)^2 . \qquad (5)$$

where $I \approx I_p$ is the total light intensity.

Using Eq.(4) $|n_2| = 1$ cm^2/W is estimated for $G = 4$ and $I = 30$ mW/cm^2. Our estimation for n_2 is smaller than the constant reported for LCLV operating in the visible spectrum range[15]. However even this constant $|n_2| = 1$ cm^2/W is so large that it ensures refractive index modulation $\Delta n \approx 0.007$ at our experimental conditions, as it is estimated using Eq.(4).

Many devices with LC operate better with large pretilt of LC molecules. It is obvious that with 45° pretilt in LCLV the largest spatial refractive index modulation is produced because the same tilt of LC molecules around 45-degrees position results in the largest refractive index change as compared to all other alignments. It looks natural that appropriate pretilt may be introduced in LCLV by appropriate voltage bias. However this is true only in part. The strong narrow-angle scattering is observed in the studied GaAs-based LCLV even with low voltage bias of the order of a couple of volts. Such scattering is a result of recording of multiple gratings by pump light and light scattered from imperfections in the substrate and LC. The diffraction from these multiple gratings produces strong narrow-angle optical noise. Because of large refractive index modulation this noise is large and makes almost impossible precise intensity measurements for small intersection angles between the recording beams. That is why for operation with low optical noise we limit the voltage to $U_0 = 2.6$ V in most experiments.

At the same time to check possible improvement of the gain in GaAs-based LCLV the gain is measured for different rotation angles θ of the cell (see Fig. 2). Experimental data are shown in Fig. 5a by squares for normalized gain $G(\theta)/G(\theta=0)$ measured at grating spacing $\Lambda = 160$ μm. The data demonstrate that the gain may be increased at least two times with optimal alignment of LC molecules.

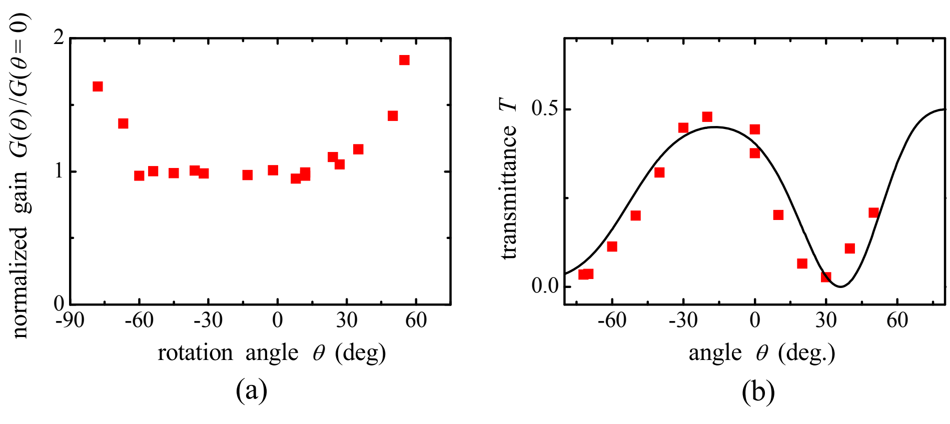


Figure 5. (a) – normalized gain as a function of rotation angle θ of the LCLV around vertical axis; (b) – transmittance of the system polarizer-LCLV-analyzer as a function of the rotation angle measured experimentally (squares) and calculated according [16] for $d = 11$ μm and $\delta = 5°$.

Asymmetry of the dependence in Fig. 5a with respect to $\theta = 0$ is expected. Such asymmetry results from nonzero pretilt of LC in our LCLV. To estimate this pretilt we placed the cell between crossed polarizer and analyzer again and measured pretilt using well-known rotation method[16], i.e., measure of the transmittance as a function of tilt angle θ. Experimentally measured transmittance is shown in Fig. 5b by squares. The solid line represents the calculation[16] with LC thickness $d = 11$ μm and LC pretilt angle $\delta = 5°$. Although our LCLV cell demonstrates the nonzero pretilt of LC molecules, this pretilt is far from optimal and therefore the gain may be increased.

4. CONCLUSIONS

The dynamic grating recording in the infrared is achieved in GaAs-based LCLV. The gain $G > 4$ is measured for small contrast wave mixing. This gain is larger than the gain reported for photorefractive-LC hybrids sensitive in the infrared[17]. Using experimental data the characteristics of the LCLV as a nonlinear optical device are estimated, namely, light-induced Δn, n_2, and LC pretilt. It is demonstrated that a further increase of the gain is possible via reducing the optical scattering from the LCLV cell components and with optimizing the pretilt of LC molecules.

5. ACKNOWLEDGEMENTS

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