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Development Of Optically-Addressed Liquid Crystal Spatial Light Modulators (OA SLM) Operating In Reflective Mode With Diameter 50 Mm Using A-Si:C:H Photoconductors And Nematic And Ferroelectric Liquid Crystals

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Dr. Vladimir A. Berenberg

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Research Institute for Laser Physics
14 Birzhevaya line
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14. ABSTRACT

This report results from a contract tasking Research Institute for Laser Physics as follows: The goals of the project are to develop the technology for and master the replication of rewritable holographic devices (optically-addressed liquid crystal spatial light modulators, OA LC SLMs) to be used for real-time correction of optical distortions in imaging optical systems. SLMs using both nematic and ferrroelectric LCs are promising for use as correctors in imaging optical systems. For the SLMs with ferroelectric LCs, high values of refresh rate can me realized (100 Hz and more), together with a relatively high diffraction efficiency (theoretically - up to ~ 40%) for non-polarized reading radiation.
The project objectives are to develop OA LC SLMs operating in the reflective mode having a diameter of 50 mm utilizing nematic and ferroelectric LCs, with a clear aperture of 45 mm, an optical quality of better than one quarter of a wavelength, an operating wavelength of 500 to 700 nm, a readout wavelength of 530 nm, and a net optical efficiency of 20% or greater.

15. SUBJECT TERMS
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Annual Report ISTC Project #2101p

" ***Development of optically-addressed liquid crystal spatial light modulators (OA SLM) operating in reflective mode with diameter 50 mm using a-Si:C:H photoconductors and nematic and ferroelectric liquid crystals***"

Research Director of the
of the SIC Vavilov SOI
for the directions of laser
physics and technique /A.A. Mak/

Project Manager /V.A. Berenberg/

St.Petersburg

2005

1. Title of the Project/Number of Annual Report

Development of optically-addressed liquid crystal spatial light modulators (OA SLM) operating in reflective mode with diameter 50 mm using a-Si:C:H photoconductors and nematic and ferroelectric liquid crystals. Annual Report #4.

2. Contracting Institute

Institute for Lasers Physics (ILP) Federal State Unitary Enterprise «Scientific and Industrial Corporation "Vavilov State Optical Institute"» (SIC Vavilov SOI)
Address: Institute for Lasers Physics, Birzhevaya line, 12, St.Petersburg, 199034, Russia.

3. Participating Institutes

Federal State Unitary Enterprise Vavilov State Optics Institute (Vavilov SOI)
Address: Federal State Unitary Enterprise Vavilov State Optics Institute, Birzhevaya line, 12, St.Petersburg, 199034, Russia

4. Project Manager

Dr. Vladimir A. Berenberg, Ph.D., Leading Scientist - Institute for Lasers Physics.
Address: Institute for Lasers Physics, Birzhevaya line, 12, St.Petersburg, 199034, Russia
Phone: +7-812-3285734
Fax: +7-812-3285891
E-mail: berenberg@mail.ru

5. Commencement Date, Duration

1 September 2001, 60 months.

6. Brief description of the work plan: objective, expected results, technical approach

The objective of the Project is the development and manufacturing of OA SLM on the basis of the nematic liquid crystals (NLC) with the diameter 50, 80, and 100 mm operating in reflective mode and providing recording of holographic grating with the amplitude up to 2π.

During the 4th year of work it is planned to manufacture, to test, and to give the Partner two items OA LC SLMs with diameter 50 mm.

The achievement of the posted goals is provided by the following activities:

- experimental and numerical investigations of the influence of the contact potential differences onto photoconductor's photosensitivity in the red spectral range under variation of parameters of the layers, neighboring with the photoconductor;
- mastering of the technology of deposition of the thin doped layers, optimizing the contact potential difference, and determining the rate of OA LC SLM sensitivity improvement;
- mastering of the technology of fabrication of OA SLM with the dual-frequency LC;
- fabrication of two specimens of OA SLM with the dual-frequency LC with diameter 50 mm. Mastering of regimes of SLM control and testing their characteristics.

7. Technical progress during the year of reference

The work is completed in full correspondence with the objectives of work and the working plan of the 4th year. The following results were obtained:

- In was shown in experiment that in the range of low (~ 1 V) voltages the layers, contacting with a-Si:C:H, provide significant influence onto the outlook of the V-A characteristic in the illuminated state. In particular, for the voltages 0.5-1 V the photosensitivity of the structure Si:C:H/a-C:H can vary in several times, depending upon the type of ITO conductivity.
- It was established, that, disregarding the preliminary evaluations, the doping of photoconductor results in decrease of photosensitivity of the reflective OA LC SLM. Possible reason is washing out of the influence of the contact potential differences onto voltage distribution in SLM in the case of feeding by the alternating voltage.

- There was revealed the abnormal variation of phase retardation in OA LC SLM with the doped photoconductor under the low illumination intensity. The growth of the illumination intensity first results in reduce of phase retardation (the voltage, applied to LC, decreases), reaches its minimal value and only with the further increase of the illumination intensity starts to grow again. This effect is observed for the definite range of feeding voltage frequencies.
- There was mastered the technology of deposition of the polyimide layer onto the transparent electrodes and the dielectric mirrors. Such a layer is chemically inert with regard to LC, does not change its electrical conductivity and provides the opportunity to feed simultaneously the LC layer by low and high frequency voltages of sufficient magnitude.
- It was proposed to feed simultaneously the OA LC SLM by low and high frequency voltages so as to reduce significantly the switching-on time. It was established that such a way of LC control is applicable in the case of low electric conductivity of LC. Thus it is impossible to use the alignment layers on the base of polyvinyl alcohol (the latter results in 5-10 times' growth of LC electrical conductivity).
- There were fabricated, tested and delivered to the Customer two specimens of OA SLMs with diameter 50 mm and with dual-frequency LC.

8. Current technical status

For the moment of compiling the annual report. the plan of the 4^{th} year of work is fulfilled completely. The correction of the plan is not necessary.

9. Cooperation with foreign collaborators

The role of the Partner is to provide financial support and interface with laboratories of the USA. The scope of the cooperation with the Partner is determined by mutual coordination of tasks to be solved and other conditions of the Project.

10. Perspectives of future developments of the research/technology developed

According to the results of the 4^{th} year of work a mutual decision was achieved by the Partner and by the Contractor of the work to prolong the Project for one more year with the goal of improvement of the reversivity of the reflective OA LC SLM with the phase modulation depth of at least 2π up to, at least, 25 Hz by means of using LC with the dual frequency control and/or with the high birefringence.

Attachment 1

Technical Annual Report Project #2101p: ***Development of optically-addressed liquid crystal spatial light modulators (OA SLM) operating in reflective mode with diameter 50 mm using a-Si:C:H photoconductors and nematic and ferroelectric liquid crystals***.

1. Introduction

Earlier the Contractor has fabricated the laboratory specimens of reflective OA LC SLMs with the diameter up to 100 mm, providing the depth of phase modulation of at least 2π at the wavelength 633 nm. However, the growth of the SLM surface has resulted in growth of the power of laser source, providing the record of holographic grating with the amplitude of ~2π, up to 30-40 mW. In addition, the reversivity of SLM was not better than 2-5 Hz.

That is why during the 4^{th} Year of the Project were investigated the opportunities to increase the OA LC SLM sensitivity by means of photoconductor doping. There was also mastered the technology of fabrication of OA SLMs with the dual-frequency LC, whose use provides the principal opportunity to shorten the time of SLM switching out. There were carried out the experiments, which have revealed the problems to be solved so as to provide the improvement of OA SLM reversivity by means of using the dual-frequency LC. This Report presents the results of the said investigations.

2. Experimental and numerical investigation of influence of the contact potential difference (for various parameters of the layers, neighboring with photoconductor) onto photoconductor sensitivity in the red part of spectrum

The increase of photosensitivity of OA LC SLM is especially important for the case of SLM clear aperture increase. The specific feature of reflective SLMs is that in the case of irradiation of photoconductor (PC) layer the voltage, applied to it, grows in just 1-2 V. This variation of the voltage is comparable with the contact potential difference between a-Si:C:H, light blocking layer (BL) and ITO layer. In principle, one can control the magnitude and sign of the contact potential difference. For instance, the contact potential difference can have different sign, depending upon the type of ITO conductivity. Variation of the contact potential difference at the boundary of a-Si:C:H and BL is determined by the characteristics of the starting stage of BL layer growth. Hence, one can provide the control over the voltage – current dependence (VCD) of irradiated PC in the range of small voltages by means of directed changing of the magnitude and sign of the contact potential difference.

In the first approximation the variation of the magnitude and sign of the contact potential difference will reveal itself in variation of the VCD shape for various polarity of the control voltage and for various photocurrent values. Deviation of the VCD shape from the linear one will result in distortion of the shape of the voltage, controlling the SLM (the higher frequency harmonics will arrive).

The theoretical investigation of the structure a-Si:H was most comprehensive for the solar panels' purposes. Among the most detailed calculations one can specially note the papers by M. Hack and M. Shur [1, 2]. However, special feature of solar panels simulation is that in their case the layers of a-Si:H are not thick (in the terms of ratio of diffusion length and the specimen thickness), while the voltage, still equal to several Volts, is not small (in the terms of ratio of drift length and specimen thickness). Hence it is impossible to use directly the results of the said works.

One can use for description in first approximation of the photoelectric properties of the structures on the base of a-Si:C:H the simplified model of the self-PC, where is observed the generation of the free charge carriers (electrons and holes) due to the light absorption. The excess transient concentration of free charge carriers induces the photoconductivity. Its specific value σ_{ph} is determined from the formula:

$$\sigma_{ph}=e\mu_n\Delta n+ e\mu_p\Delta p,$$

Here e>0 is the charge of electron; μ_n and μ_p are the electrons' and holes' mobility; Δn and Δp are transient concentrations of electrons and holes. The values of Δn and Δp can be determined from the continuity equation. In the stationary approximation under the condition illumination of PC layer with the thickness d by the beam of monochrome light (homogeneous distribution across section, frequency ν and intensity P_o) the said equations look like follows (in the assumptions of linear process of recombination, of equal lifetime of electrons and holes τ and neglecting the boundary effects – one-dimensional approximation):

$$\frac{d^2\delta n}{dz^2}=\frac{dV}{dz}\cdot\frac{d\delta n}{dz}-\delta n\cdot[\delta p-\delta n-q_L^2\cdot(V-V_c)]+\gamma\cdot\delta n-\kappa\cdot I\cdot\exp(-\kappa\cdot z),$$

$$\frac{d^2\delta p}{dz^2}=-\frac{dV}{dz}\cdot\frac{d\delta p}{dz}+\delta n\cdot[\delta p-\delta n-q_L^2\cdot(V-V_c)]+q\cdot[\gamma\cdot\delta p-\kappa\cdot I\cdot\exp(-\kappa\cdot z)],$$

$$\frac{d^2V}{dz^2}=q_L^2\cdot(V-V_c)-\delta p+\delta n,$$

where δn, δp, V, I are the nondimensional normalized values of transient concentrations of electrons and holes, of electric field potential and of the light fluency density at the PC surface, V_c - are the nondimensional normalized contact potential difference. The following formulae couple the dimension values Δn and Δp, U, P_o of the said parameters with their dimension-less values:

$$\frac{\Delta n}{\delta n}=\frac{\Delta p}{\delta p}=\frac{kT}{e}\cdot\frac{\varepsilon_o\varepsilon}{ed^2},\ \frac{\mathrm{U}}{\mathrm{V}}=\frac{kT}{e},\ \frac{P_o}{I}=\left(\frac{kT}{e}\right)^2\cdot\frac{\varepsilon_o\varepsilon}{ed^2}\cdot\frac{h\nu\mu_n}{\beta d},$$

Here k is the Boltsman constant, T is the PC temperature, ε_o is the dielectric permeability of vacuum, ε is the relative dielectric permeability of PC, β is the quantum yield of photo effect, hν is the energy of light quantum. Other parameters, met in the equations, are determined from the relationships:

$$\gamma=\frac{e}{kT}\cdot\frac{d^2}{\mu_n\tau},\ q=\frac{\mu_p}{\mu_n},\ q_L=\frac{d}{L_o},\ \kappa=\alpha d,$$

Here L_o is the Debay screening length, α is the coefficient of light absorption by PC.

The system of equations is solved for the following boundary conditions:

$$\delta n|_{z=0,1}=\delta p|_{z=0,1}=0,\ V|_{z=o}=V_1,\ V|_{z=1}=V_2,$$

Here $V_{1,2}$ are the potentials of the electric field, applied to PC.

Several photosensitive structures ITO/a-Si:C:H/a-C:H with different technology of ITO and blocking layer deposition were fabricated for experimental confirmation of the influence of the magnitude and sign of the contact potential difference onto PC photosensitivity. The VCD of these structures in the illuminated state were measured by the method of Hg-drop under irradiation by the tungsten lamp with the intensity ~ 100 mW/cm^2.

Fig.1 illustrates the influence of ITO fabrication technology onto VCD.

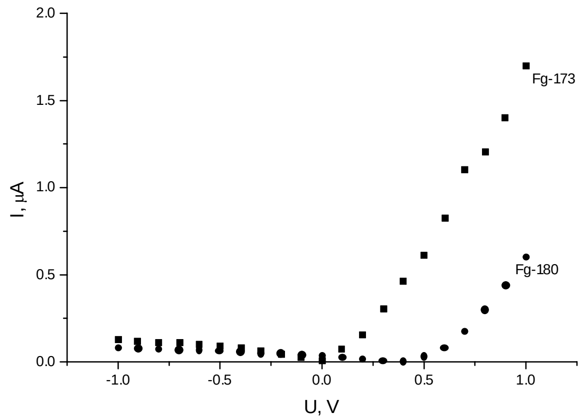


Fig.1. The influence of the ITO conductivity type onto VCD of the photosensitive structure of ITO/a-Si:C:H.

One can see from the data in the Fig.1, that the photosensitivity of structures with various ITO layers has different value for the positive voltages. For instance, the photocurrent of the specimen FG-173, whose ITO layer, unlike that of the specimen FG-180, was deposited in the oxygen atmosphere, is much larger than that of the specimen FG-180 for the positive voltages, applied to Hg-drop. Note that the fabrication regimes and the parameters of photosensitive layer a-Si:C:H were one and the same. The specimen FG-180 reveals the shift to the positive bias range (0.4 V) of the point of zero current. Such a shift is an evidence of the presence of the internal field in the absence of the external voltage. The only difference of these two specimens was related to ITO layers, hence, one can decide that these two specimens are characterized by the different values of the contact potential difference at the boundary ITO/a-Si:C:H. The shift of the zero current point to the range of positive voltages indicates that the contact potential difference at this boundary is negative for the specimen FG-180. Hence, the ITO layer here is working as the n-type semiconductor. The specimen FG-173 reveals practically zero shift of the negative current. This is an evidence of the ohmic connection type of the contact (the contact potential difference is nearly zero). For the voltage ~0.5 V the photosensitivity values of the specimens FG-173 and FG-180 differ in the order of magnitude.

Fig.2 illustrates the influence of variation of the contact potential difference at the boundary a-Si:C:H/ a-C:H onto VCD.

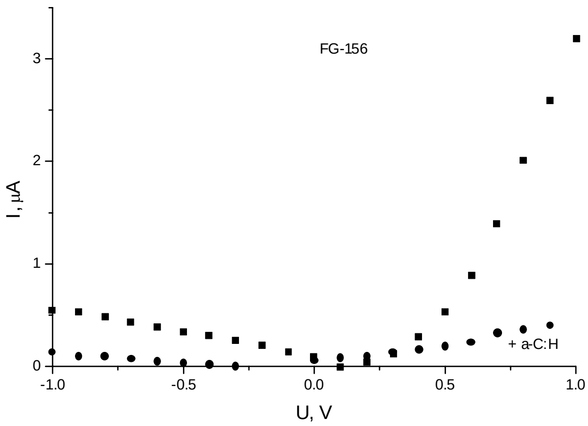


Fig.2. The influence of the blocking layer onto VCD of the structure ITO/a-Si:C:H/a-C:H.

The VCD of the starting specimen without light blocking layer have had the minor (~0.1 V) shift of the zero current to the range of the positive voltage. The deposition of the light blocking layer of a-C:H resulted in formation on the boundary a-Si:C:H/a-C:H of the negative contact potential difference. As a result, the zero current point was shifted to the range of negative voltages in some ~0.3V, i.e. the layer of a-C:H played the role of n-type semiconductor.

Hence, it was confirmed by the experiment, that in the range of small voltages (~ 1 V) the layers, contacting with a-Si:C:H, influence significantly onto the voltage-current dependence in the illuminated state. In particular, for the voltages of 0.5-1 V the photosensitivity of the structure ITO/a-Si:C:H/a-C:H can vary within the range of several times depending upon the ITO conductivity type.

3. Mastering of technology of deposition of the thin doped layers, optimizing the contact potential difference. Evaluation of improvement of OA LC SLM sensitivity

The thin (~ 20 nm) layers of a-Si:C:H, doped by boron and phosphorus, were deposited before and after deposition of photoconductor (PC) a-Si:C:H, whose thickness was ~ 3 μm. The concentration of boron and phosphorus was such, which have provided the maximal conductivity of layers. The doped layers were deposited under the following main technological parameters:

pressure in reactor	0.2-0.3 Tor,
expenditure of 100% silane	5-7 sccm,
expenditure of mixture of 10% methane in argon	40-50 sccm,
expenditure of 10% doping mixtures of phosphine or diborane	0.5-2 sccm,
substratum temperature	240^o-250^o C,
specific RF power	~ 0.1 W/cm^2,
deposition time	2 min.

After deposition of the first doped layer of a-Si:C:H and before PC deposition the reactor was evacuated for 2-3 hours down to the residual pressure (2-4)10^{-6} Tor. Thus was reduced the rate of the non-controlled doping of PC by the remainders of dopant at the reactor walls. When the doped layer was deposited over PC layer, the content of methane in the gas mixture was increased up to 40-45% so as to prevent the current flow along this layer.

The typical voltage-current characteristic (VCC) of the fabricated structures are shown in the Fig.3 and 4. Worth mentioning, that for the similar structures the photocurrent can differ in 2-3 times both due to non-controlled variation of parameters during fabrication and to variation of the surface of the mercury contact from one measurement to another.

In the Fig.3 are shown the darkness VCC for the various types of structures: the structure ITO-p-i-n-Hg drop (Fg 183), the structure ITO-i-Hg drop (Fg 187) and the structure ITO-p-i-Hg drop (Fg 188); here p, i, n correspond to the layers doped by boron, non-doped and doped by phosphorus. In the same Figure the solid curves show the calculated values of the capacity currents for the frequencies 100 and 1000 Hz for the structures with the thickness 3 μm and the square, equal to the square of the mercury contact (~0.3 mm^2).

One can see from the Fig.3, that the range of alternating voltages, where the darkness currents are less than the capacity currents and where OA LC SLM can be controlled by light, strongly depends upon the type of the structure. Introduction of the doped layers leads to the narrowing of the said range of voltages, because in this case are produced the strong darkness direct currents, caused by the increase of efficiency of injection of the corresponding charge carriers from the contacts (the holes for the p-type and the electrons from the n-type of doping). The narrowest range is revealed by the p-i-n structure. For the structure without the thin doped layer of n-type (Fg 188) the said range is wider (the direct darkness current is less than that for p-i-n structure (Fg 183). The maximal width of the said range of voltages is revealed by the self-PC (Fg 187).

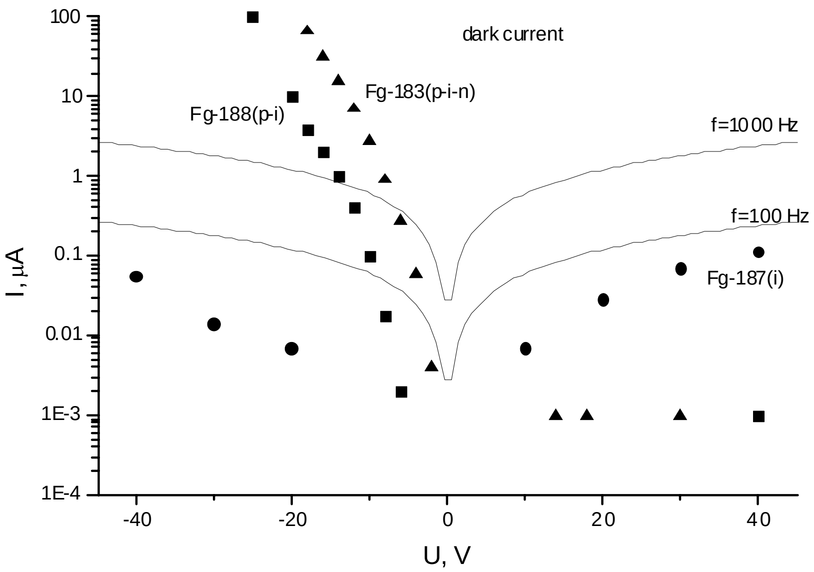


Fig.3 The darkness voltage-current curves of the structures with various rate of doping

In the Fig.4 are shown the VCC of the illuminated structures in the range of small (less than 1 V) voltages. The specimens were illuminated by the tungsten lamp with the intensity ~ 100 mW/cm^2.

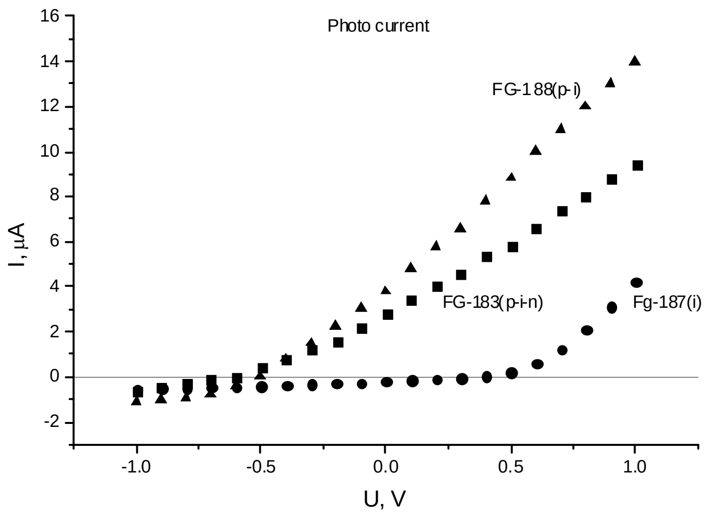


Fig.4 The voltage-current curves of the illuminated structures with various rate of doping

It is seen from the curves in the Fig.2, that in the range of voltages from 0 to 0.5 V the photocurrents in the doped structures are much stronger than that in self-PC. However, the increase of the voltage leads to the reduce of difference in photocurrents' strengths between various types of structures.

Hence, the analysis of VCC shows that use of the structures with the doped contact layers can lead to the increase in OA LC SLM sensitivity in the case, when the potential difference at PC layer is not more than 0.5 V.

To investigate the influence of PC doping onto OA LC SLM photosensitivity we have fabricated three structures without the doped layers and two structures with the doped layers – namely, p-i-n and p-i structures. The dependence of phase retardation $\Delta\Phi$ vs. PC illumination intensity was measured at the setup, shown in the Fig.5. The value of $\Delta\Phi$ was determined from the measurements of reflectivity of SLM in the crossed polarizers P_1. The said reflectivity was measured with the use of sounding laser 1 radiation (wavelength 633 nm). PC was illuminated by the He-Ne laser 2 (wavelength 633 nm), whose radiation was modulated in time (exposure duration 2-3 sec, period 6 sec). Smooth variation of intensity of laser 2 radiation was provided with the use of polarizer P_3 and of the LC twist-cell, controlled by the voltage U_2. The intensity of radiation of the laser 2 was measured by means of photodiode PD_2 and voltmeter V. The intensity of PC illumination was measured by the photodiode PD_1 and by oscilloscope OS_2. The diameter of the light spot at PC was ~7 mm. The rate of intensity fluency inhomogeneity across the spot was within 3-5%. The maximal fluency of radiation intensity at PC was ~2 mW/cm^2.

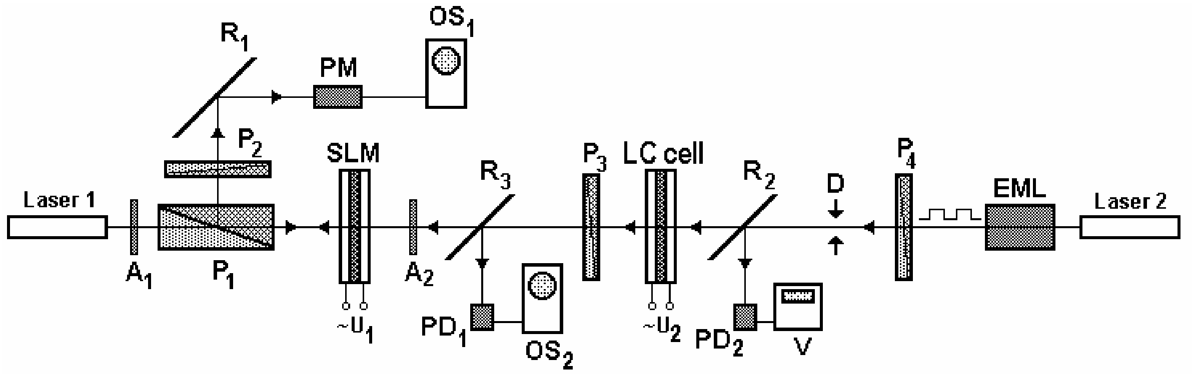


Fig.5. The scheme of measurement setup: $A_{1,2}$ – the calibrated filters, P_{1-4} – polarizers, R_{1-3} – mirrors, D – aperture, EML – the electro-optical light modulator, LC cell – the LC twist cell, $PD_{1,2}$ – photodiodes, PM – photomultiplier, $OS_{1,2}$ – oscilloscopes, V – voltmeter.

The value of the reflectivity coefficient R(U,I) of OA LC SLM in crossed polarizers for the sounding light in general case is described as:

$$R(U,I)=\frac{1}{4}\left[\left\{\sqrt{R_{\parallel}(U,I)}-\sqrt{R_{\perp}}\right\}^2+4\sqrt{R_{\parallel}(U,I)R_{\perp}}\sin^2\{\frac{\Delta\Phi(U,I)}{2}\}\right]\sin^2(2\varphi),$$

here $R_{\parallel}$ and $R_{\perp}$ are the OA LC SLM reflectivity coefficients for the light, polarized parallel and perpendicular to the director projection onto the substratum plane, φ is the angle between the sounding light polarization plane and the director projection onto the substratum plane, $\Delta\Phi$ is the controlled phase retardation, U and I are the voltage of OA LC SLM feeding and the intensity of illumination spot at PC. According to the measurements, for variation of U the value of reflectivity coefficient $R_{\parallel}$ oscillates with the practically equal amplitude from R_{min} to R_{max}. The reflectivity coefficient $R_{\perp}$ is within the range: $R_{min} \le R_{\perp} \le R_{max}$. The ratio $q=R_{max}/R_{min}$ depends upon the reflectivity of the dielectric mirror inside SLM, upon the coefficient of radiation attenuation in the transparent electrode, upon optical and geometry characteristics of SLM, passed through by the sounding radiation. For the investigated specimens of OA LC SLMs the value of the coefficient q was not more than 1.5 times. One can easily see, that for such values of coefficient q the difference between the normalized value of reflectivity coefficient R(U,I) and $\sin^2(\Delta\Phi/2)$ is less than 1%.

In the Fig.6-9 are shown the results of measurement of dependencies of phase retardation ΔΦ upon the PC illumination intensity I for the fixed effective values of the sinusoidal feeding voltage U. The value of the voltage U was chosen such, which has provided the nearly maximal value of phase retardation for I≈2 mW/cm^2. The measurements were carried out for the feeding voltages U with the frequency 0.5 and 1 kHz.

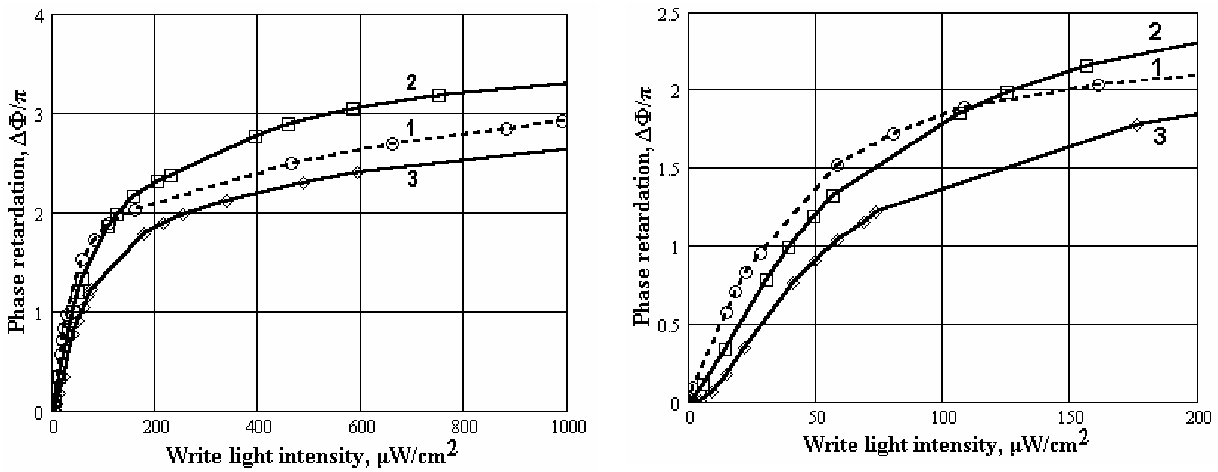


Fig.6. Dependence of phase retardation vs. light intensity for 3 specimens of OA LC SLM with self-PC, fed by voltage with the frequency 1 kHz: U=2.44 V (1), 2.54 V (2), 2.96 V (3).

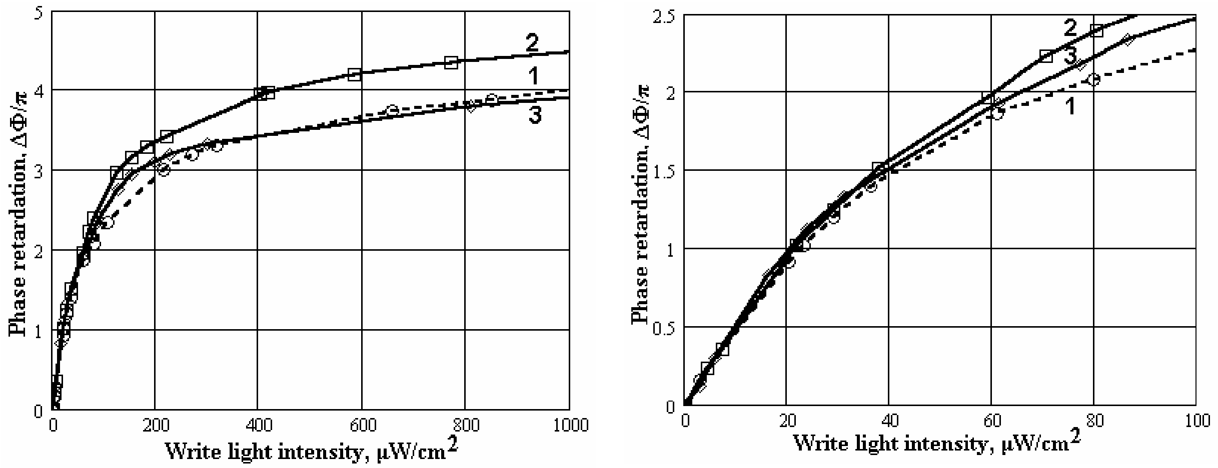


Fig.7. Dependence of phase retardation vs. light intensity for 3 specimens of OA LC SLM with self-PC, fed by voltage with the frequency 0.5 kHz: U=2.94 V (1), 2.92 V (2), 2.6 V (3).

The results of measurements of the SLM specimens with self-PC, shown in the Fig.6 and, illustrate the rate of reproducibility of OA LC SLM parameters. One can see from these curves, that for lower frequencies of the control voltage U the difference between the SLM specimens in the range, where ΔΦ<2π, is reduced.

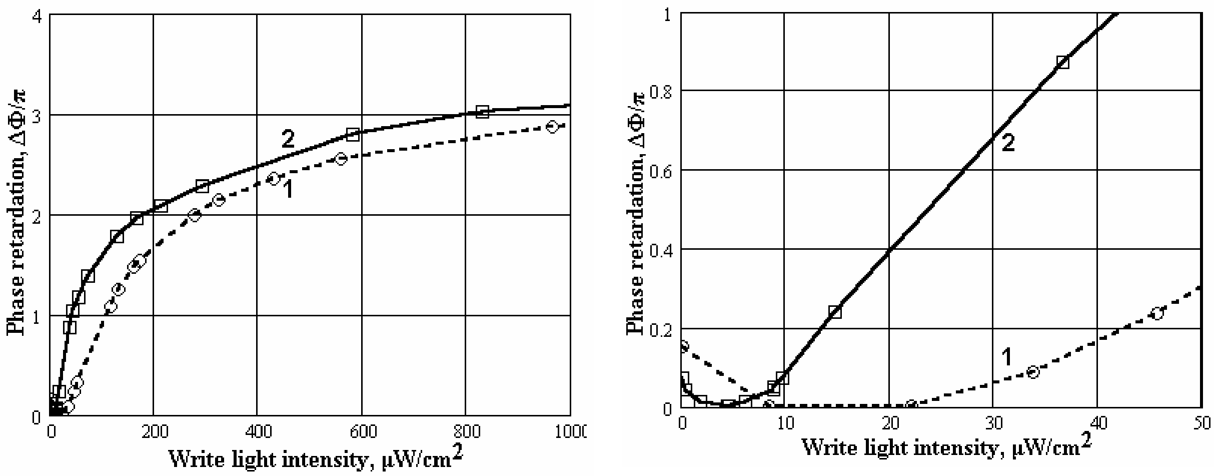


Fig.8. Dependence of phase retardation vs. light intensity for specimens of OA LC SLM with p-i-n structure (1) and p-I structure (2), fed by voltage with the frequency 1 kHz: U=2.65 V (1), 2.96 V (2).

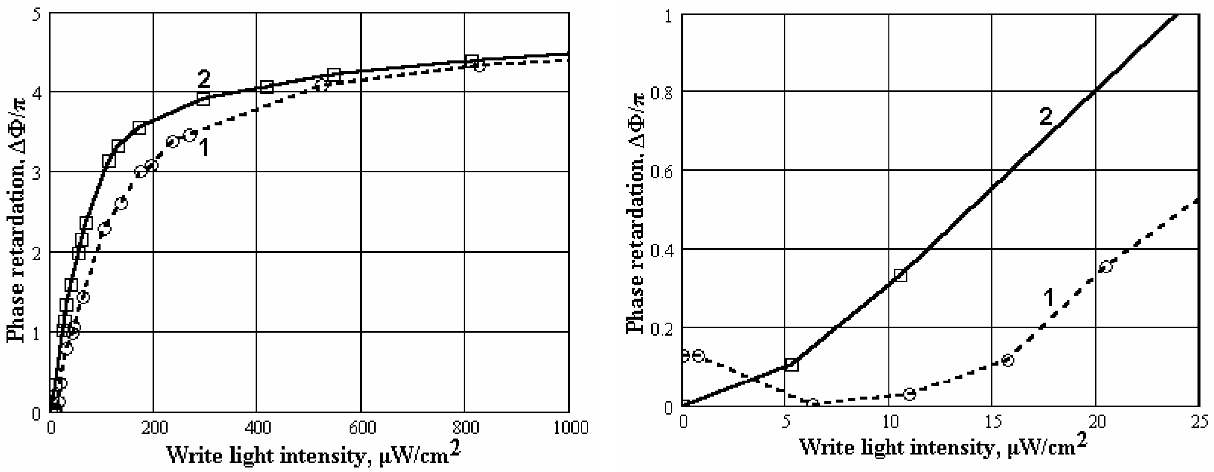
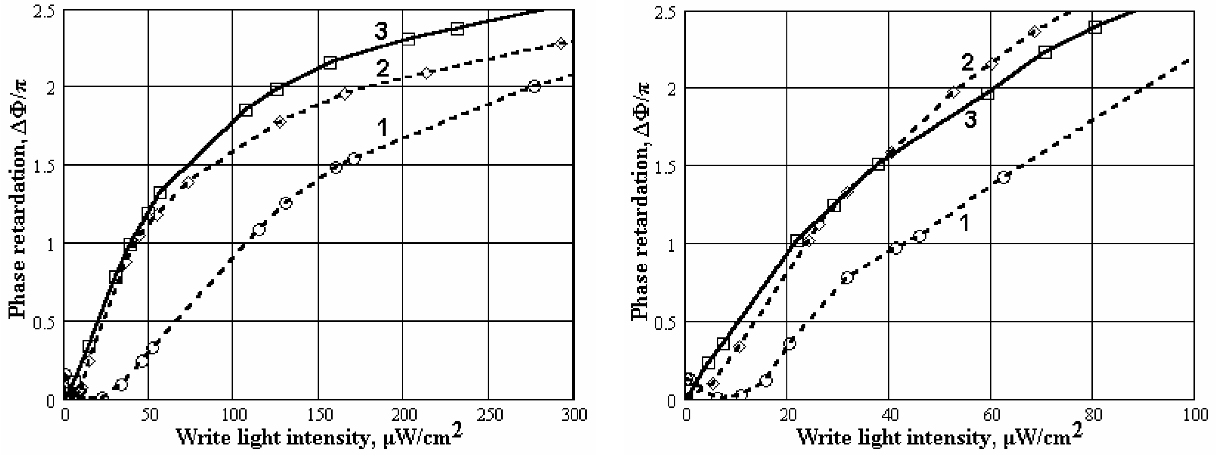


Fig.9. Dependence of phase retardation vs. light intensity for specimens of OA LC SLM with p-i-n structure (1) and p-I structure (2), fed by voltage with the frequency 0.5 kHz: U=2.93 V (1), 3.04 V (2).

One can see from the curves in Fig. 8 and 9, that for the small intensity of the illumination radiation the phase retardation reveals the abnormal behavior. The increase of the illumination intensity results first in the reduce of the phase retardation (the voltage, applied to the LC layer, decreases), then the retardation reaches the local minimum, and only in the case of further increase of illumination intensity it starts to grow. This effect is observed within some range of feeding voltage frequencies.

The comparison of photosensitivity of OA LC SLMs with self-PC and with p-i-n and p-i structures shows, that doping reduces the SLM sensitivity. The difference of OA LC SLM photosensitivity values grows with the increase of the feeding voltage and can be as high as ~ 2 times. It is illustrated by the Fig.10.



a b

Fig.10. Difference of photosensitivity of OA LC SLM specimens with self-PC (3), p-i-n (1) and p-i (2) structures, fed by voltage with the frequency 1 kHz (a) and 0.5 kHz (b).

4. Mastering of technology of OA SLM with dual frequency controlled LC

It is well known that the use of S-effect in the nematic LC is the most advantageous for the record of the phase holographic gratings with the predetermined fringe shape. S-effect is realized in the LC media with the positive dielectric anisotropy, when the primary orientation of the director is planar or close to planar. Application of the electric field results in re-orientation of LC, which tends to reach the state with the minimal energy – the one, where the director is collinear to the electric field. After switching the electric field off the LC reveals the self-relaxation to the primary sate under the action of the viscosity – elasticity forces.

The simplified analysis [3] results in following relationships, which make it possible to evaluate the switching-on time τ_{on} and switching-off time τ_{off} of the S-effect for the case of small deviation of the director from its equilibrium position and for the planar orientation of the director:

$$\tau_{on} = \frac{\tau_{off}}{U^2/U_{th}^2 - 1}, \qquad \tau_{off} = \frac{\gamma_1 d^2}{\pi^2 k_1},$$

here $U_{th} = \pi\left(\frac{k_1}{\varepsilon_0 \Delta\varepsilon}\right)^{1/2}$ is the threshold value of voltage for the S-effect, ε_0 is the dielectric permeability of vacuum, $\Delta\varepsilon$ is the value of the anisotropy of the dielectric permeability of LC, k_1 is the elasticity coefficient for the S-effect, γ_1 is the viscosity coefficient, d is the thickness of LC layer and U is the voltage, applied to LC.

There are two important consequences from these relationships; these consequences are valid also for the case of not small deviation of the director from its equilibrium position, when it is necessary to take into account the so-called back-flow effect in LC, i.e. the hydrodynamic flow, accompanying the re-orientation of LC molecules [4]. These consequences are as follows:

1. One can make the switching-on time τ_{on} rather short (<1 ms) by application to the LC layer of the voltage, which is sufficiently higher than U_{th}.
2. Switching times are proportional to the square of the LC layer thickness and depend upon the viscosity – elasticity ratio γ_1/k_1.

The idea of the dual frequency addressing of LC is as follows. In this case the LC is not switched on by external force (voltage), but is also switched off by the voltage application, resulting in restoration of the starting conditions. In this case one has to apply the voltage with the frequency, providing the negative value of $\Delta\varepsilon$ [5]. In this case the value of τ_{off} is determined by the equation, similar to that, valid for τ_{on}. Usually the value of $\Delta\varepsilon$ reveals the weak dependence upon the frequency of the voltage, applied to LC. The critical value of the voltage frequency f_c, at which the value of $\Delta\varepsilon$ changes its sign, is usually equal to several or several dozen MHz [6]. But in the LC medium for the dual frequency addressing the comprising it components are chosen so as to provide the shift of f_c to the frequency range of ~(5-10) kHz. Such a choice results in some limitations of the properties of such LC. In particular, they reveal the relatively high viscosity and strong temperature dependence of the critical frequency f_c [6].

The possibility of significant shortening of the switching time was shown in numerous papers on the examples of LC-cells or of the electrically addressed LC SLMs for light modulation, implementing S-effect or twist-effect. In particular, in [7,8] were demonstrated the switching-on and off times of ~ 5 ms with the feeding by low and high frequency voltage of ~ 50 V. Yet faster switching of LC cell was demonstrated in [9]. For the feeding voltage of ~ 70 V the switching time was ~(0.2-0.3) ms. To the moment the dual frequency nematic LC media has not found out the wide field of application due to some special features of these LC media, but the investigations of dual-frequency LC and of the devices on their base are continued [10-12].

The fast response of dual frequency controlled LC is provided by the use of high voltages of both low and high frequency. Seemingly, that is the reason of small number of papers devoted to the use of dual frequency LC in optically addressed LC cells and SLMs [13,14]. Indeed, in the case when it is necessary to provide the gray-scale modulation, the variation of the voltage, applied to LC layer, has to be not more than ~(2-3) times with regard to the threshold value. Hence, the shortening of the response time is thus possible only by shortening the switching off time. Hence, at the first glance, it is possible to improve the response time significantly only in the case of binary amplitude or phase modulation. Exactly this approach was demonstrated in [13,14] in transparent OA LC SLMs, using the photosensitive layer metal – dielectric – semiconductor.

The reflective SLM with diameter 35 mm was fabricated for experimental investigations. The thickness of photoconductor (PC) layer was ~ 3 μm, the thickness of the mirror and the light blocking layer was ~ 1.5 μm and the thickness of the LC layer was ~ 7 μm. The LC was aligned by means of rubbing the thin layer of the polyvinyl alcohol (PVA), deposited for 1% water solution. The dual frequency LC composition LC-1001 (Russia, NIOPIK) was used. According to the data of [4], for 20^oC f_c=6.5 kHz, for the control voltage frequencies of 0.2 and 40 kHz $\Delta\varepsilon$=2 and –2 correspondingly, at the wavelength 633 nm the optical anisotropy is Δn=0.24.

The dynamic of time response of OA LC SLM in its dependence upon intensity of PC layer illumination was investigated on the setup, shown in the Fig.5. We have registered the time dependence of the reading-out radiation, reflected by SLM, placed between two crossed polarizers, when PC was illuminated by light pulses. It is known that the intensity of radiation, reflected by SLM, is ~$\sin^2(\Delta\Phi/2)$, where $\Delta\Phi$ is the phase retardation variation. The writing in and reading out radiation wavelength was 633 nm. The spot of writing in radiation had the diameter of ~ 7 mm, while that of reading out was ~ 3 mm. the reading out was monitored in CW mode, while the writing in radiation intensity was modulated in time by the rectangular-shaped pulses with duration (1-2) sec and the repetition rate ~ 0.2 Hz. The duration of the forward and backward fronts of the light pulse was ~ 1 ms.

The SLM was controlled in the following manner. SLM was continuously fed by the low frequency voltage (frequency 1 kHz), whose amplitude was chosen from the requirement to provide $\Delta\Phi\approx2.5\pi$ for the maximal possible illumination of PC layer. SLM was switched off by the pulse of high frequency voltage (frequency 40 kHz), synchronized with the backward front of the writing-in light pulse. The amplitude and duration of this high-frequency pulse was chosen from the condition of provision of the minimal switching off time for $\Delta\Phi\approx2.5\pi$. The results of experiments are shown in the Figures 11 and 12. The parameters of the high-frequency voltage pulse (amplitude and duration) were one and the same for results in Fig.11 and Fig.12.

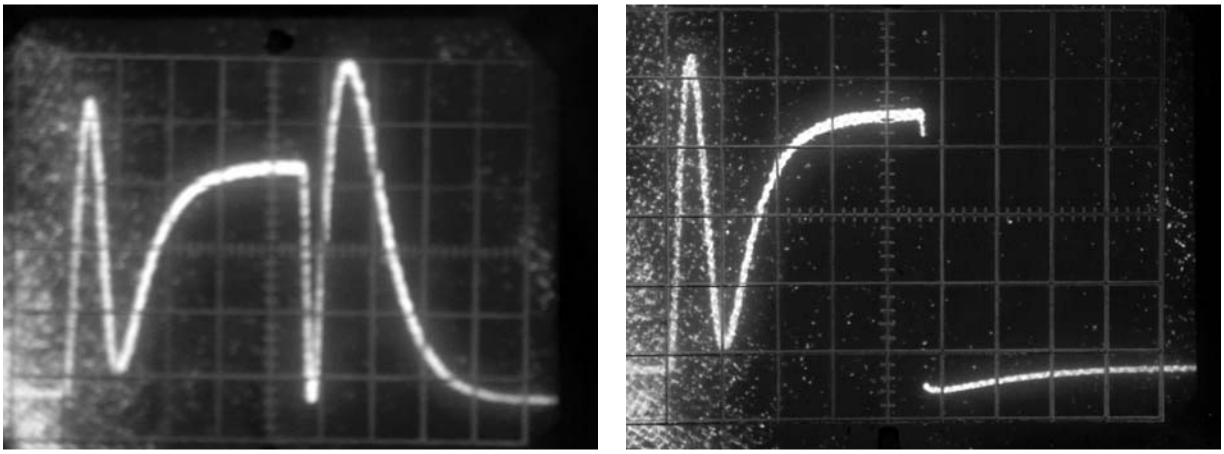


Fig.11. Oscillograms of the time response of SLM with $\Delta\Phi \approx 2.5\pi$ without switching by the external force and in the case of switching-off by the high frequency pulse (1 unit = 0.2 sec).

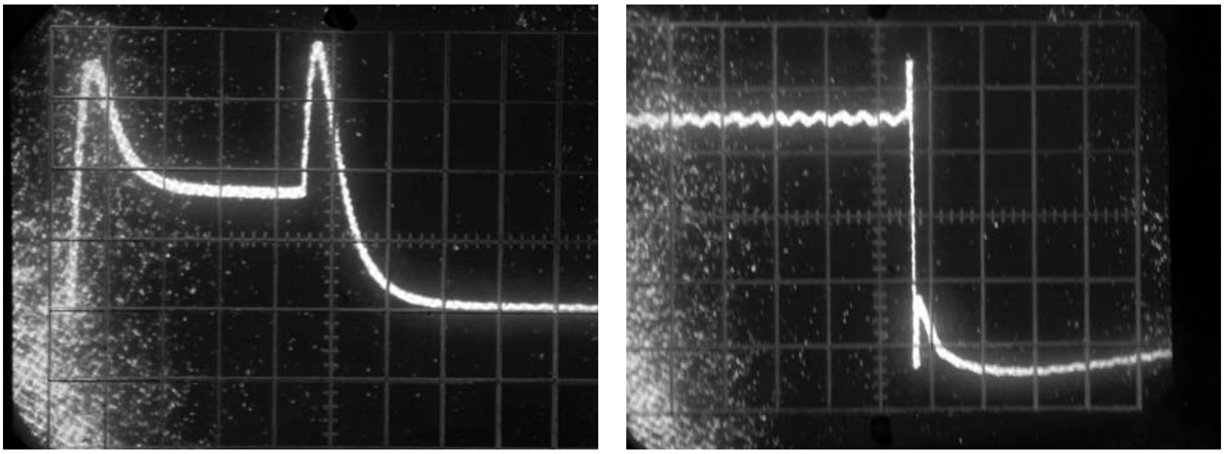


Fig.12. Oscillograms of the time response of SLM with $\Delta\Phi \approx \pi$ without switching by the external force (1 unit = 0.5 sec) and in the case of switching-off by the high frequency pulse (1 unit = 50 ms).

One can see from the Fig.11 that for the constant level of PC illumination one can make the switching-off time the negligibly short in comparison with the switching-off time by proper choice of the amplitude and duration of the high frequency pulse. In this case the real time of SLM switching off was equal to 20 ms. However, in the case of variation of the illumination intensity and for the same switching off pulse one can observe the rather durable transient process. The reason is lack of correspondence between the switching-off pulse amplitude and the depth of voltage modulation at LC. One more reason is the presence of the voltage over U_{th} at the non-illuminated reflective LC SLM.

Hence, one can draw a conclusion from the results of experiments, that the improvement in the response time of the reflective OA LC SLM for the record of holographic gratings with the predetermined fringe profile due to the use of switching-off by the short high frequency voltage pulse cannot be too high due to the relatively long time of SLM switching-on.

One can shorten the switching on time in the case when the maximal possible value of $\Delta\Phi$ is much higher than that required for gratings record. Special feature of the OA LC SLM performance is that for given intensity of illumination of PC the bias voltage, applied to LC, is chosen from the requirement of provision of the working point at the curve of $\Delta\Phi(U)$ at the place of its most fast growth. In this case usually the voltage at LC is not much more than U_{th}. This is the main reason of the comparatively durable switch-on time. However, in the case of excess resource of $\Delta\Phi$ one can reduce the range of $\Delta\Phi$ down to required value and thus increase the bias voltage at LC. In this case the ratio of the control voltage to its threshold value will grow, and τ_{on} will be shorter. In the case of using the dual frequency LC the required effect can be achieved by simultaneous application to SLM of the low- and high-frequency voltage. In the Fig.13 are shown the calculated dependencies of $\Delta\Phi/\Delta\Phi_{max}$ ($\Delta\Phi_{max}=2\pi\cdot\Delta n\cdot d/\lambda$, where λ is the wavelength of the reading-out radiation) vs. the mean square value of low-frequency voltage U^{lf}_{rms} (measured in terms of the threshold value U^{lf}_{th}) in the absence and in the presence of the high-frequency voltage U^{hf}_{rms}.

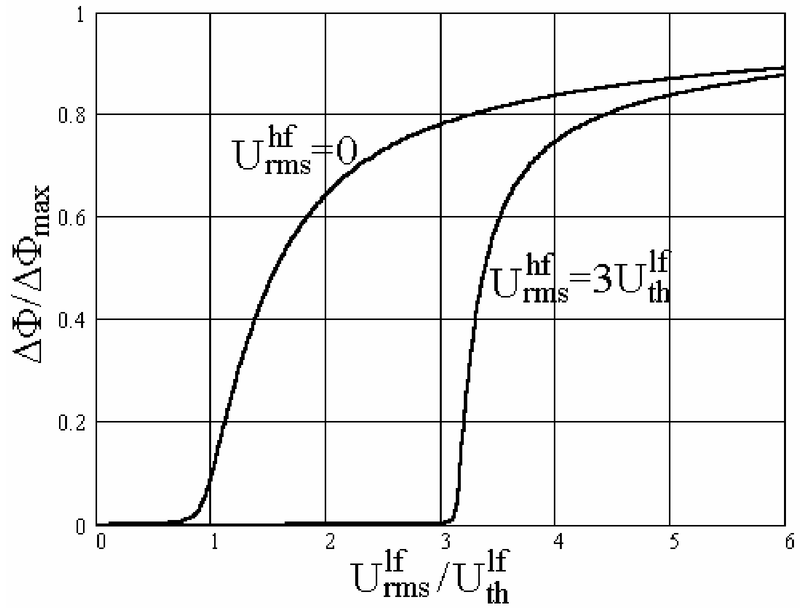


Fig.13. Dependence of phase retardation upon low-frequency voltage in the case of simultaneous action of low- and high-frequency voltage onto LC layer.

One can see from the Fig.13 that it possible to realize the significant shift of the range of low-frequency voltage, used for the phase retardation control, to the higher voltage region. This shift is in principle limited by the electric strength of SLM and by the admissible level of Joule losses. Such an approach to OA LC SLM control provides some new opportunities. One can, for example, reduce either the time of SLM switching on or the intensity of the writing-in radiation, providing the required value of phase retardation $\Delta\Phi$. In this case it possible also to use the methods of LC alignment without rigid connection with surface, when the dependence of the angle of director tilt upon voltage is sharper [15], but the starting tilt of the director is large.

The application of such a method of control to the described specimen of OA LC SLM has resulted in the unexpected effect. Already at the not very high voltages of 20-30 V there was observed the strong scattering, which is usual for LC with the increased electric conductivity. Special experiment have shown that the contact of LC compositions, which we have used (BL006, BL037 and LC-1001), with PVA layer results in increase of the electric conductivity of LC in (5-10) times in comparison with its starting value. That is why it was necessary to master the technology of deposition of the polyimide layer (which is chemically inert with respect to LC) for LC alignment.

It was shown in several papers that polyimide (PI) layers provide stable orientation of various LC compositions, that they are transparent in the visible spectral range, are chemically inert with regard to LC and are stable under the action of electric field and temperature. That is why they are widely used for LC displays' production. The companies Nissan Chemical, Japan Synthetic Rubber Co, Merck and others have developed the polyimide compositions for alignment of various types of LC media. Upon the recommendations of the people, involved into design of LC displays, we have used the electric isolation lacquer AD 9103 of Russian production. It is a solution polypiromellitamid acid (PA) in dimethylformamide. The PI layer is produced by means of thermal imidization of the lacquer layer. Direct application of the technology of PI layer production, which was developed for LC displays' production, to the case of OA LC SLMs is hardly possible, because the thermal processing has to be carried out at the temperatures, which are too high for photoconductor that is why the technology of PI layer production was modified.

The lacquer was dissolved by dimethylformamide in the ratio (1:10 – 1:20) so as to provide the optimal kinetic viscosity, equal to (1.5-2.5)·10^{-6} m^2/sec. The dissolved lacquer was deposited onto the surface by the method of the stretched meniscus with the further centrifugation. The speed of the centrifuge rotation was ~ 3000 rotations per minute, the duration of centrifugation was (20-25) seconds. The thickness of thus produced layer was (500-700) Å. The thermal imidization of the layer was carried out in the air atmosphere in the drying chamber. The layer was first gradually heated up to some (230-240)^{o}C during 1 hour, and then stayed under this temperature for 2 hours.

Thermally processed PI layer was then mechanically ribbed by the cotton manufacture. The ribbing was carried out so as to provide the uniform relief of the micro grooves across the surface. Several LC cells and OA LC SLMs were thus produced, which were filled by various LC compositions. It was found out that the PI layer does not modify the electric conductivity of LC, and the intense scattering, observed in the case of simultaneous feeding of dual-frequency LC by low and high frequency voltages, is absent.

5. Fabrication of two specimens of OA SLM with dual frequency controlled LC with diameter 50 mm. Mastering of SLM controls regimes and testing of parameters

Special scheme was prepared for mastering the regimes of control of OA SLM with the dual-frequency LC. It has provided the opportunity to sum the low and high frequency voltages at SLM for the conditions of the independent variation of amplitudes of both voltages within the wide range. The experiments have confirmed all the conclusions about the possibility to control the characteristics of OA LC SLM, which were made upon the results of calculations. Provision of the possibility to realize the significant excess of $\Delta\Phi$ the switching on time of SLM was increased in at least one order of magnitude. However, no significant change of the switching off time was observed in this case. The shortening of the SLM switching off time requires delivery of the additional pulse of control voltage, as it was described earlier.

In accordance with the Work Schedule there were fabricated two experimental specimens of OA LC SLMs with diameter 50 mm. There was measured the depth of phase modulation and the diffraction efficiency for the irradiation by radiation of He-Ne laser (wavelength 633 nm) and reading out by radiation with the wavelength 532 and 633 nm.

The depth of phase modulation was measured with the use of the experimental setup, similar to the one, described in the Annual Report #1 (Year 2002). The photoconductor (PC) was irradiated by radiation, whose intensity was time modulated (exposure 2-3 sec, period 6 sec). The diameter of the spot on PC was ~ 7 mm. The inhomogeneity of the intensity across the spot was not more than 3-5%. The maximal intensity of radiation at PC was equal ~4 mW/cm^2. The reading out was carried out by the low intensity beam of He-Ne laser with the diameter ~ 3 mm. The OA LC SLM was fed by sinusoidal voltage with the frequency from 0.5 to 10 kHz. According to the measurements the maximal phase retardation in the experimental specimens was ~~(2.5-3)π.

The diffraction efficiency was measured for the formation of the grating with the symmetrical fringe profile, depending upon the spatial frequency of the grating, of the control voltage parameters and writing-in radiation intensity. The diffraction grating was recorded by two converging plain beams of He-Ne laser radiation. The diameter of the grating was ~10 mm.

The hologram was read-out by the low intensity radiation of He-Ne laser. The diameter of the reading out beam was equal 8 mm.

The OA LC SLM was fed by the rectangular bi-polar pulses with the amplitude U_{pp}, with the repetition rate f=1/T and ratio of duration to the period 1:2. In the Fig.14, 15 are shown the results of measurement of DE for two specimens of SLMs in the case of hologram recording approximately in the center of OA LC SLM. The curves in the Fig.14, 15 were taken for the spatial frequency of the grating 16 lp/mm.

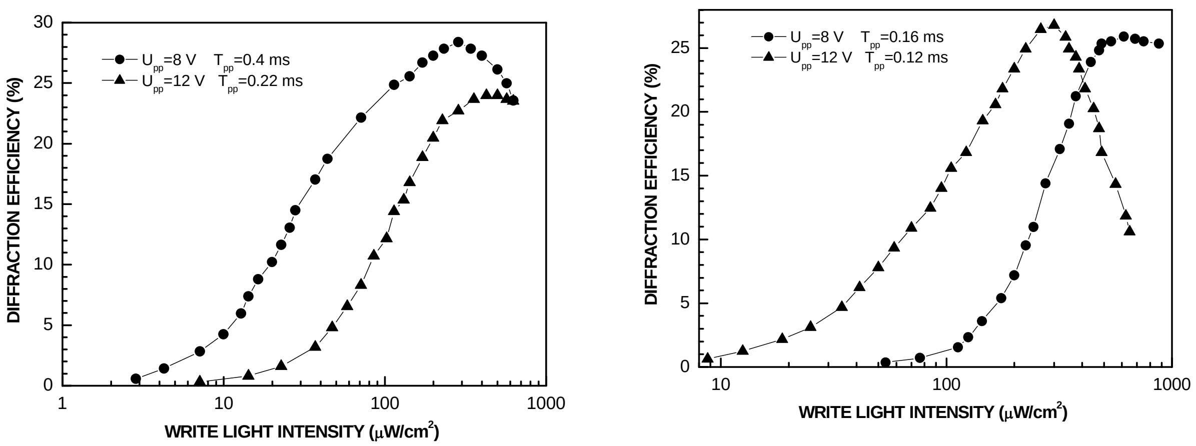


Fig.14. Dependence of the diffraction efficiency vs. intensity of recording radiation in one of two interfering beams for the specimens #1 and 2.

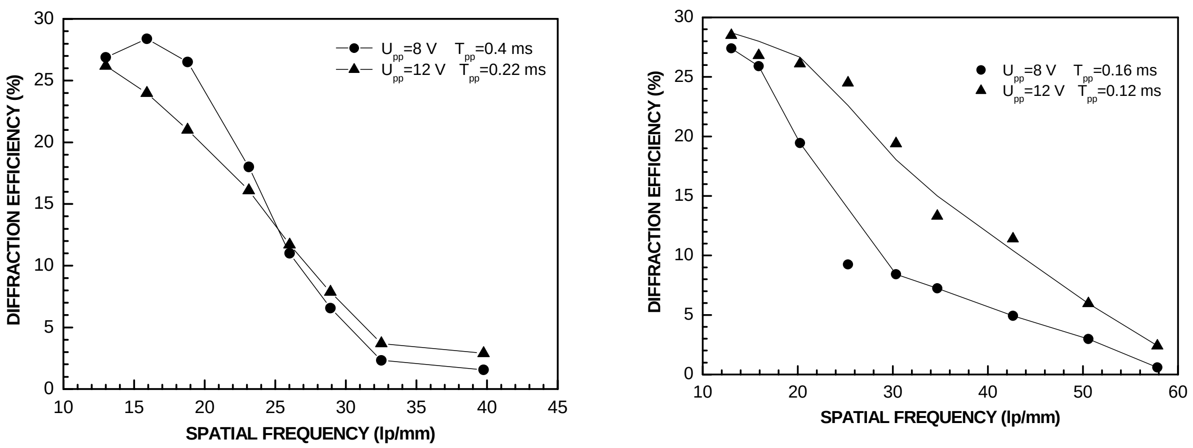


Fig.15. Dependence of the diffraction efficiency vs. spatial frequency of holographic grating for the specimens #1 and 2.

In the Figures 14 and 15 are presented the physical values of DE (without account for the losses of reading-out radiation during reflection by the dielectric mirror.

6. Conclusion

The following results were obtained in course of investigations:

- It was confirmed by the experiment, that in the range of small voltages (~ 1 V) the layers, contacting with a-Si:C:H, influence significantly onto the voltage-current dependence in the illuminated state. In particular, for the voltages of 0.5-1 V the photosensitivity of the structure ITO/a-Si:C:H/a-C:H can vary within the range of several times depending upon the ITO conductivity type.

- It was found out, that, to the contrary to the preliminary estimations, the photosensitivity of the reflecting OA LC SLM photoconductor reduces with doping. Possible reason is, probably, the grading of the influence of the contact potential difference onto the voltage distribution in SLM in the case of feeding by the alternating voltage.
- It was found out that the OA LC SLM with the doped photoconductor reveals the abnormal variation of the phase retardation under the low intensities of illumination. The increase of the illumination intensity results first in the reduce of the phase retardation (the voltage, applied to the LC layer, decreases), then the retardation reaches the local minimum, and only in the case of further increase of illumination intensity it starts to grow. This effect is observed within some range of feeding voltage frequencies.
- There was mastered the technology of deposition of the polyimide layer onto the transparent electrodes and dielectric mirrors. This layer is chemically inert with regard to LC, it does not vary the electric conductivity of LC and makes it possible to feed LC by significant voltages of low and high frequency simultaneously.
- It was proposed to feed the OA LC SLM by the low- and high-frequency voltage simultaneously with the purpose of significant shortening of the switching on time. It was found out that this approach is applicable in the case of low electrical conductivity of LC. That is why the use of alignment layers on the base of polyvinyl alcohol is not admissible, because this approach results (5-10) times increase of electric conductivity of LC Two specimens of OA SLM with dual-frequency LC and diameter 50 mm were fabricated, tested and delivered to the customer.

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Attachment 2

Resume of the papers, published during the reported Year

1. Vladimir Yu Venediktov, Vladimir A. Berenberg, «Phase conjugation systems on the base of optically addressed liquid crystal spatial light modulators for CW and quasi-CW lasers», Program of 5th Workshop on Adaptive Optics in Industry and Medicine, Beijing, China, August 28 – September 1, 2005.

There were analysed possible schemes of phase conjugation of CW and quasi-CW lasers with the use of OA LC SLMs with the account for their real characteristics.

2. Vladimir A. Berenberg, Nikolay N. Freygang, Alexey A. Leshchev, Yury A. Petrushin, Pavel M. Semenov, Michael V. Vasil'ev, Vladimir Yu. Venediktov, «The system of phase conjugation with a two-stage holographic corrector recording scheme», 5th Workshop on Adaptive Optics in Industry and Medicine, Beijing, China, August 28 – September 1, 2005, Proc. SPIE, vol. 6018, (to be published).

The results were presented of experimental investigations of the dynamic phase conjugation of the weak laser radiation via the record of the phase corrector in OA LC SLM with the use of opto-electronic channel of interferometery information transfer.

Attachment 3

Summary of personnel commitments for the year and equipment acquired during the year.

1. Summary of personnel commitments for the year

	Worked out (men/days)	Sum ($)
Category I:	**1113.0**	**29116.00**
Category II	**477.5**	**11460.00**
Category III:	**0**	**0**
Category IV:	**0**	**0**

2. Equipment acquired during the year

Item	Name
1	LC monitor BENQ FP767-12
2	Keyboard Genius SlimStar
3	Mouse Logitech Premium Optical