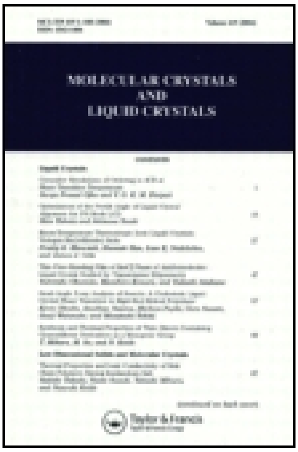


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# Liquid Crystals in Spatial Light Modulators

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# LIQUID CRYSTALS IN SPATIAL LIGHT MODULATORS

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ABSTRACT. Spatial light modulators (SLM) are miniature high-resolution devices of optical processors and displays. The influence of various physical parameters of a LC material on the SLM optical response, speed of response and other information characteristics is considered. The possibility of the optical memory in SLM and non-linear optical control is also discussed.



## 1. INTRODUCTION

The spatial light modulators (SLM) are intended for transformation of images in terms of spectrum, coherency and light power. First of all they were designed as basic elements of optical processing of great information files. The SLMs may also be used successively in high- brightness projectors as light anplifiers. A lot of various SLM constructions was proposed earlier. They are described in Refs. 1-5. The construction of an optically addressed (OA) SLM based on metal-dielectric-semiconductor (MDS)-LC structure is shown in Fig. 1. As powerful light beam samples a LC layer, the last one is separated from a semiconductor by a dielectric mirror and lightblocking ("black") layer. These layers are absent in SLM when it is used for reversal writing of holograms. Both an input image and a reference beam are incident on semiconductor through the LC layer. The SLMs based on MDS-LC srtuctures are widely used in analizers of Fourier spatial spectrum, in image correlators with joint Fourier transformation, the image transformers of grey-scale X-ray exposures to pseudocolor [1-3]. Currently the design of displays and TV systems of collective and individual use based on SLM and compact ERT is actively under way. These arrays are attractive because of the absence of unfavourable radiation . Some SLM parameters (output image contrast ratio or difraction efficiency, speed of response) were districted by LC properties. The goal of this article is a review of different ways of improving of a SLM output parameters by a right choice of a LC material or electrooptic effect. The influence of various semiconductor characteristics and spatial noise in SLM is considered in [6-8].

## 2. OPTICAL RESPONSE OF AN OA SLM.

An intensity of a transformed image in every point is a function of the phase difference between extraordinary and ordinary rays ( $I_{out} \sim \sin^2(\Delta\Phi(U_{LC})/2)$ ), but a contrast of the transformed image and an intensity of spatial spectrum depend only on another phase difference of extraordinary ray in points, which correspond a distinction of a level of input illuminance. It is clear from following speculations. Let the phase difference in points of a LC aperture, which correspond a non-illuminated point of semiconductor and an illuminated point is equal $\Delta\Phi_d = (2\pi L/\lambda)[n_e(U_d) - n_o]$ and $\Delta\Phi_L = (2\pi L/\lambda)[n_e(U_L) - n_o] = \Delta\Phi_d + (2\pi L/\lambda)\delta n_e = \Delta\Phi_d + \delta\Phi$ respectively.

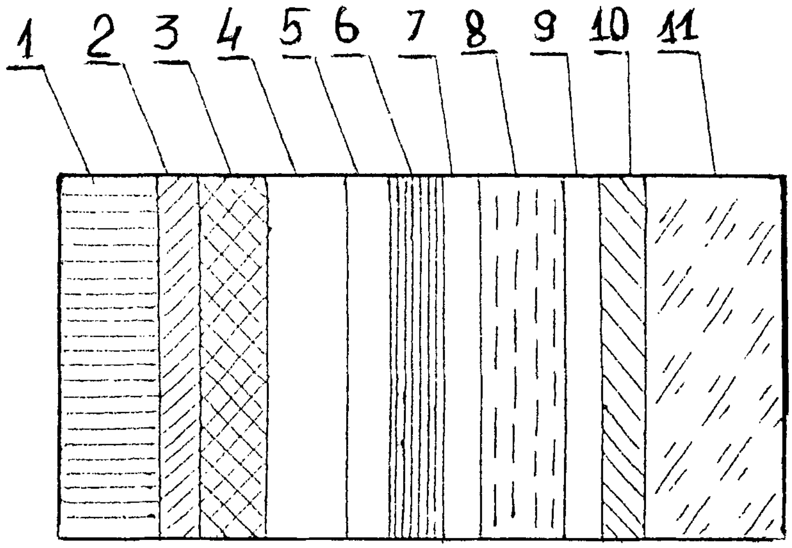


Fig. 1. The arrangement of SLM, consisting of MDS-LC structure. 1 - glass- fiber plate ; 2, 10 - transparent ITO electrodes ; 3 - dielectric mirror ( optical glue or SiO ) ; 4 - photoconductor (GaAs or a-Si:H) ; 5 - light-protecting layer (CdTe) ; 6 - dielectric mirror (10-14 layers of $SiO_2$ -$TiO_2$) ; 7, 9 - orientants (PVA, polyimides ) ; 8 - LC ; 11 - output glass plate .

If the bias voltage is selected so that $\Delta\Phi_d = 2m\pi$ ( m is an integer ), the transformed image intensity in other points will be proportional to $\sin^2(\Delta\Phi/2) = [\sin(\Delta\Phi_d/2)\cos(\delta\Phi/2) + \sin(\delta\Phi/2)\cos(\Delta\Phi_d/2)]^2 = \sin^2(\delta\Phi/2)$. A set of empirical expressions of dependences of phase difference at different points of SLM aperture on various parameters of controlling regime (SLM driving voltage U, input intensity I, contrast of input image K) is derived in Refs. 8, 11. These expressions are outcome of the empirical relation

$$U_{LC}/U = a + b \ln ( I/I_{th} ) \qquad (2.1)$$

It describes the experimental dependences of LC part of bias voltage on input intensity I, which succeeds the threshold intensity of SLM photosensibility $I_{th}$ (Fig. 2) ( "a" and "b" are parameters, which are functions of resistance and capacitance of LC and MDS-structure). The dependence $U_{LC}/U(I)$ is received , when corresponding dependences of phase difference $\delta_0$ of LC layer on SLM voltage U or cell voltage U are compared (Fig. 3). The LC layer works in this case like an analog voltmeter. It is shown in Refs. 8, 11 that effective value of the threshold voltage of an electrooptic effect increases in a SLM and the effective steepness of dependence of $\delta\Phi$ on U decreases when input intensity grows (Fig. 3):

$$\delta\Phi = (4\pi L/\lambda)(\delta n_e/\delta U_{LC})[ a + b \ln(I/I_{th}) ]* \{ U - U_{th}/[a+b \ln(I/I_{th})]\} \qquad (2.2)$$

where at $U_{LC} \gtrsim U_{th}$

$$\frac{\delta n_e}{\delta U_{LC}} = \frac{1}{U_{th}} \frac{\Delta n( n_e + n_0 )}{n_0^2} \left( \frac{K_{33}}{K_{11}} + \frac{\Delta\varepsilon}{\varepsilon_\perp} \right)^{-1} \qquad (2.3)$$

$n_e$, $n_0$ - refractive indices, $K_{33}$, $K_{11}$ - LC elasticity constants, $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$ , $\varepsilon_\parallel$, $\varepsilon_\perp$ - dielectric constants in directions parallel and perpendicular to the LC director respectively. The expression (2.2) is simpler for small input intensities ( $I/I_{th} - 1 = \delta I << 1$ ) :

$$\delta\Phi = (4\pi L/\lambda)(\delta n_e/\delta U_{LC})( a + b \ln\delta I )* [ U - U_{th}/(a + b \ln\delta I) ] \qquad (2.4)$$

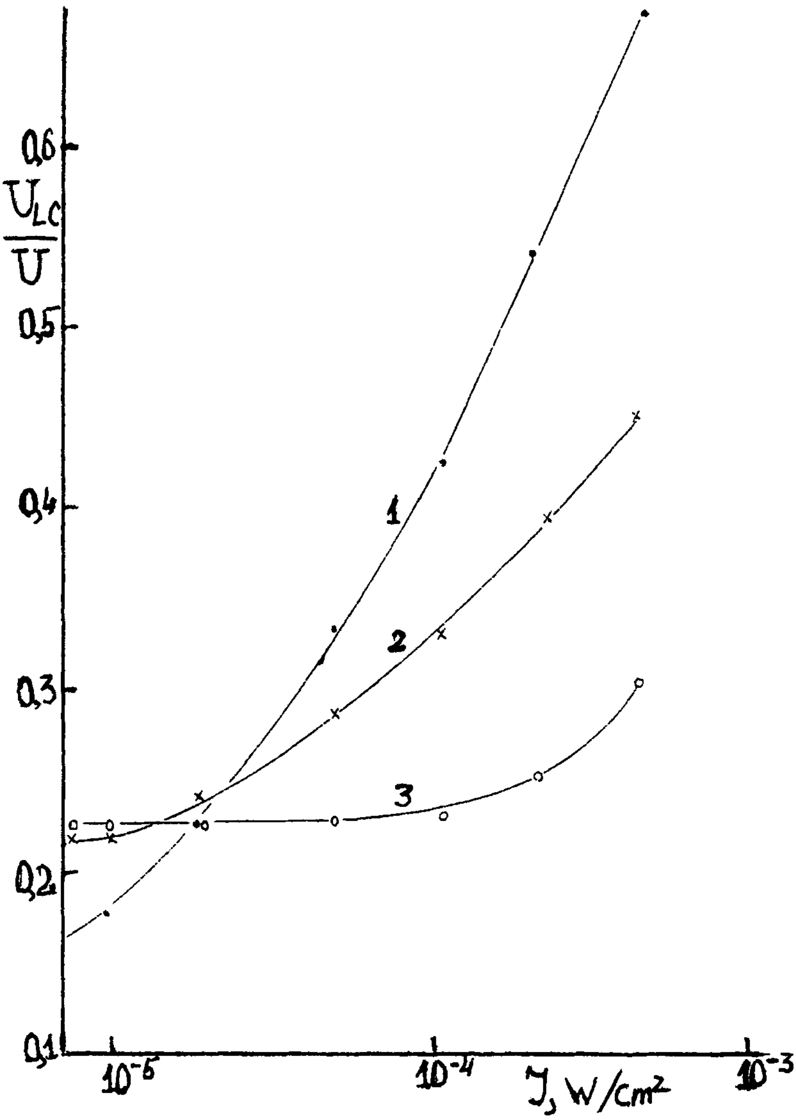


Fig. 2. The experimental dependence of ratio $U_{LC}/U$ on input intensity I at different frequencies f of driving voltage. f = 0.1 ( 1 ); 1 ( 2 ) ; 5 ( 3 ) kHz.

The maximum value of phase difference $\delta\Phi$ is determined by the expression depending on input image contrast K only:

$$\delta\Phi = (4\pi L/\lambda)(\delta n_e/\delta U_{LC})\, b\, U \ln K \qquad (2.5)$$

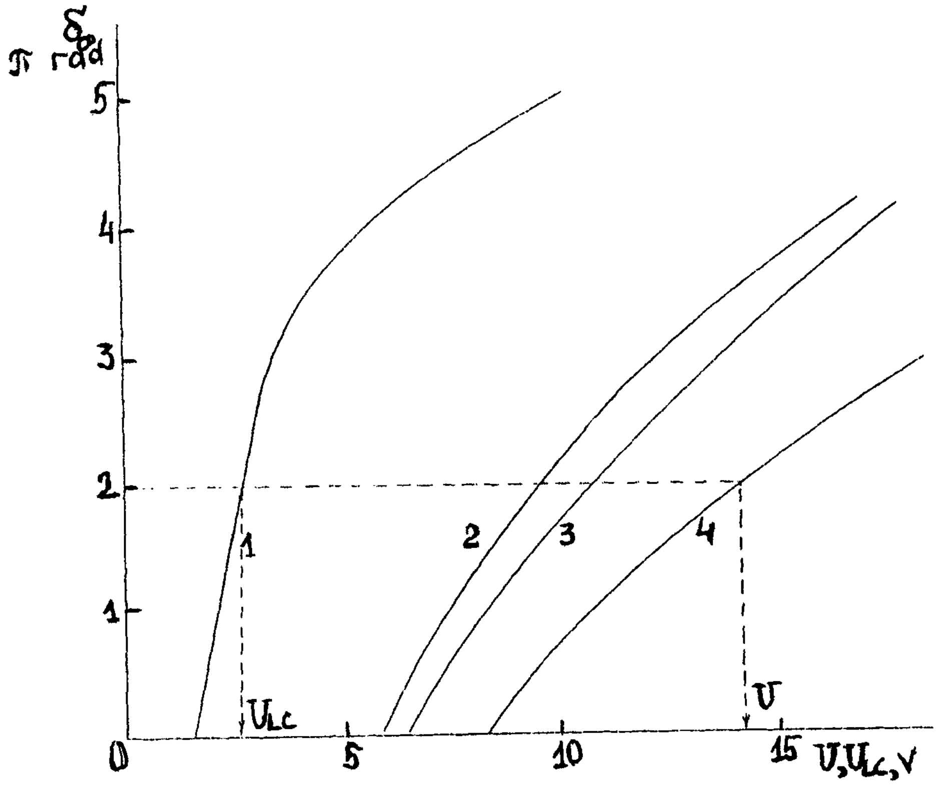


Fig. 3. The phase retardation dependence on liquid crystal bias voltage $U_{LC}$ ( 1 ) and SLM driving voltage U ( 2, 3, 4 ) at input intensities I = 0.1 ( 2 ) , 0.01 ( 3 ) , 0 ( 4 ) mWt/cm$^2$ . The discontinous lines are driven for calculation of $U_{LC}$ /U ratio at constant value of phase retardation $\delta_0$ .

which is simpler in a case of a small contrast (K - 1 << 1)

$$\delta\Phi = (4\pi L/\lambda)(\delta n_e/\delta U_{LC})\, b\, U\, (K - 1) \qquad (2.6)$$

It follows from (2.2)-(2.6) that steepness of volt-transmittance characteristics of the electrooptic effect and a part of driving voltage in a LC layer have to be increased to make higher contrast of transformed image. The steepness is expressed for ECB-effect in terms of $\delta n_e/\delta U_{LC}$ value. Its effective value reduces because of voltage drop in other dielectric layers (glue, mirror, light-blocking layer and so on).

Besides that the information characteristics of a SLM depend on speed of response of functional layers, first of all of LC layer. Therefore let us consider the influence of electrooptical and physical LC parameters on characteristics of transformed image taking into account separately the speed of response and the voltage distribution in layers of MDS-LC structure.

It is shown in Refs. 12, 13 that optical response of LC to bias voltage variation is described by the figure of merit for ECB- and DAP-effects ( in Russian literature S- and B-effects; DAP - directly aligned , i.e. homeotropic, phase ) :

$$M = ( \lambda L/ \tau_{\pi} )( U_{th} /\Delta U_{\pi}) \qquad (2.7)$$

$\tau_{\pi}$ and $\Delta U_{\pi}$ are switching time and bias voltage variation respectively, which correspond to the variation of $\Delta\Phi$ by $1\pi$ . The dependence of M on $U_{LC}$ has a maximum at $U_{LC} \sim 1,5-2\ U_{th}$, since $\tau_{\pi}$ and $\Delta U_{\pi}$ vary differently with increase of $U_{LC}$ [14]. The figure M can be transformed to the next form at $U_{LC} \rightarrow U_{th}$ for ECB ( $M_S$ ) and DAP ($M_B$ ) effects:

$$M_S = ( K_{11} / \gamma_1 )\Delta n( K_{33}/K_{11} + \Delta\varepsilon/\varepsilon_{\perp} )^{-1} \qquad (2.8)$$

$$M_B = ( K_{33} / \eta_B )\Delta n( K_{11}/K_{33} - \Delta\varepsilon/\varepsilon_{\parallel} )^{-1} \qquad (2.9)$$

where $\gamma_1$, $\eta_B$ are viscosity coefficients. The other form of figure of merit M is proposed in Ref. 15. However, the incorrect prepositions were used during the derivation.

The $M_S$ value correlates with data transmittive capacity (DTC) of a SLM channel, i.e. LC shutter, (Fig. 4). The DTC may be defined as

$$P = - ( 1/\tau_{fr} )\log ( I_2/I_1 ) = - ( 1/\tau_{\pi} )\log \sin^2(\delta\Phi/2) \qquad (2.10)$$

where we assume the minimal possible time of data variation (frame) $\tau_{fr}$ to be equal $\tau_{\pi}$ at $U_{LC} = U_{th} + \Delta U_{\pi}$ , $I_1$ and $I_2$ - intensity of SLM output signal, when input signal is present or absent respectively. The physical parameters of different NLC substances used in calculations were taken from Refs. 12 or 13. It is shown in Refs. 12, 13 that value of $M_S$ is maximal for derivatives of tolane ($12.6 \cdot 10^{-12}$ $m^2/s$) and azobenzenes ($10.8 \cdot 10^{-12}$ $m^2/s$) among the weak-polar substances, for derivatives of biphenyl ($3.8 \cdot 10^{-12}$ $m^2/s$) , pyridine ($2.4-4.0 \cdot 10^{-12}$ $m^2/s$) and

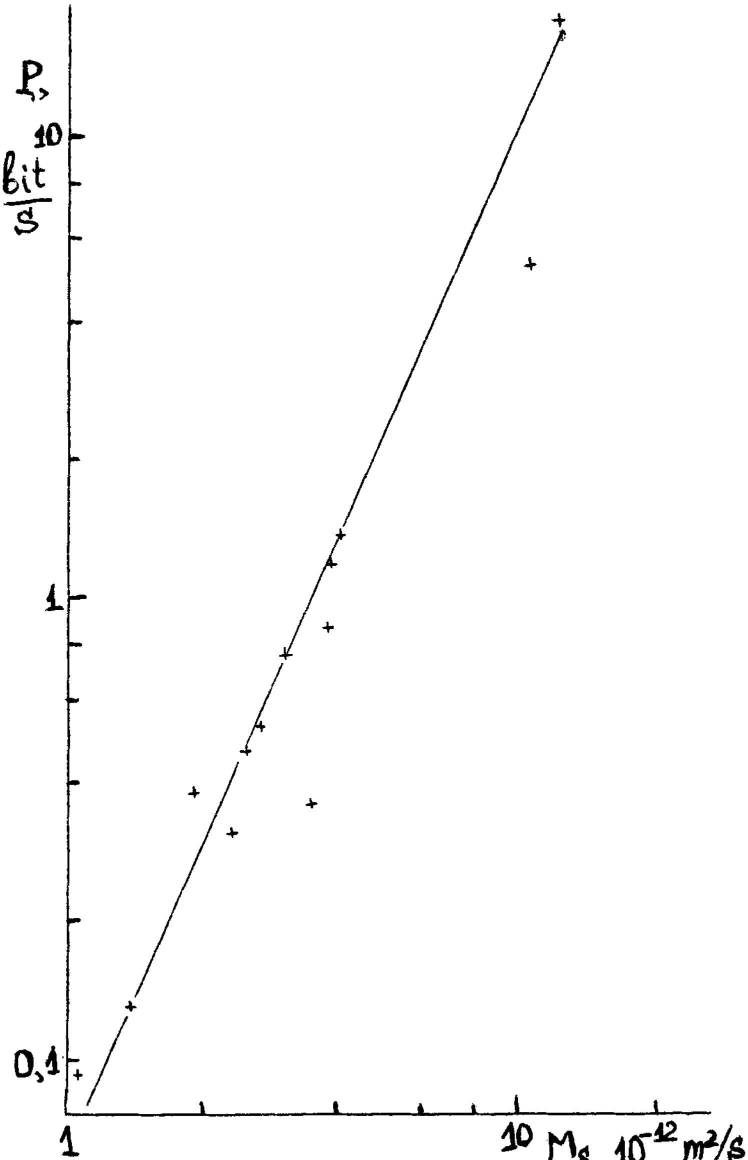


Fig. 4. The correlation of $M_S$ values ( horizontal coordinate ) and data transmmittive capacity $P$ (vertical coordinate ) for different NLC substances.

phenylcyclohexane (3.5-6.2*$10^{-12}$ $m^2$/s) among polar nematogens. Besides of that , the NLC with odd number of carbon atoms in alkyl chain and even number in alkoxysubstituents possess the most value of $M_S$(Fig.5).

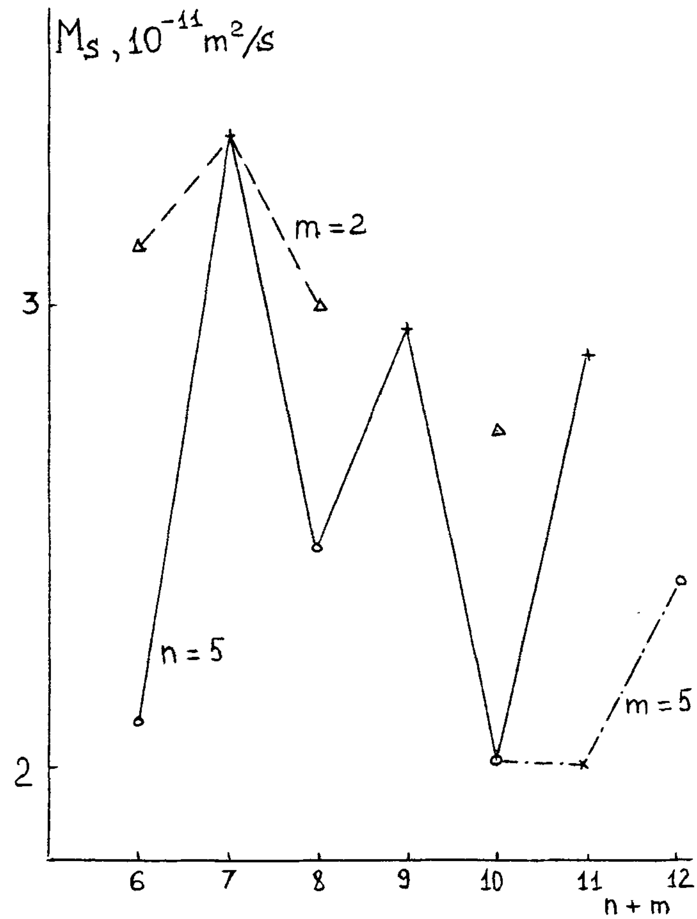


Fig. 5. The dependence of figure of merit $M_S$ on summar number of carbon atoms in alkyl- and alkoxy chains for 4-pentyl-4'-alkoxytolanes (n=5; +, o), 4-alkyl-4'-ethoxytolanes (m=2; Δ , +), 4-alkyl-4'-pentoxytolanes (m=5; o, x).

The $M_S$ maximum in mixtures of 4-heptyl-4'-cyanophenylcyclohexane (PCH-7) with azoxycompounds is achieved at concentration of PCH-7 20 % w. The dependence of NLC physical parameters on order parameter $S = S\ (1 - T/T\#)^{\beta}$ ($T\# \simeq T_{NI}$) determines their temperature dependence first of all ( any physical parameter considered ~ $S^{x}$ ). At the same time the exponents $\gamma^{x}$ of these dependences are functions of molecules polarity, length of alkyl substituents, a presence of moieties with saturated bonds [16, 17]. Because of that the position of maximum of dependence $M_S(T)$ relative to clearing temperature $T_{NI}$ is determined by a LC molecular structure. The figure $M_S$ has a maximum at a temperature

$$T_{opt} = T_{NI} ( 1 - B\beta T_{NI} /E ) \qquad (2.11)$$

where E is activation energy of NLC rotational viscosity, $\beta$- exponent of temperature dependence of order parameter S. Unlike [15] a coefficient B is a function of molecular structure. The B value varies from 0.4 for short polar molecules with great chain of conjugation to 2.1 for long polar molecules with cyclohexane or bicyclooctane moieties. The maximal deviation of $T_{opt}$ from $T_{NI}$ is for substances with great B and small E values ( e.g. weak-polar compounds ). It is useful to know the $T_{opt}$ value , when SLM is a part of optical processor operating in a wide temperature range. At the optimal regime $T_{opt}$ and maximal temperature of operating have to coincide. The driving regime with most M meaning has to be chosen.

On the base of fullfilled investigations the new LC materials (LCM) were designed for OA SLM. These LCM have high steepness of voltage-transmission curves in the visible and near IR diapasone and high speed of response. The informational characteristics of GaAs SLM based on the usually used ZhK-1282 (A) or the new mixture VK-1(B) are listed in Table 1.

Table 1

The characteristics of SLM with different LC materials measured at $U_{SLM}$ = 70 V , $I_{input}$ = 32 $\mu$Wt/sq.cm and full contrast variation ( $\delta\Phi$ = $1\pi$)

| Parameters | A | B |
|---|---|---|
| Time of response on optical pulse, ms | 120 | 12 |
| Time of relaxation , ms | 180 | 20 |
| Contrast of transformed image | 65 | 80 |
| Number of resoluble elements | 1250*1250 | 890*890 |
| Data transmittive capacity, bite/s | $6.5*10^7$ | $4.4*10^8$ |

The voltage distribution in layers of MDS-LC structure is studied theoretically and experimentally in Refs. 11, 18. The dependences of increment of bias voltage in the LC layer relative to the same increment in the photoconductor layer $\Delta U_{LC}/\Delta U_S$ on $U_{LC}$ and the similar dependences of relative change of the optical responçe $\Delta\delta/\Delta U_S$ were calculated (see Fig. 6 for $\Delta\delta/\Delta U_S$). If we know the dependence of variation of semiconductor electrical characteristics on intensity of input illuminance, we may calculate the transformation of an input image by the SLM ($\delta = (\Delta\Phi_{max} - \Delta\Phi)/\Delta\Phi_{max}$, $\Delta\Phi_{max} = 2\pi L\Delta n/\lambda$). The meanings of increments of $-\Delta U_{LC}/\Delta U_S$ and $-\Delta\delta/\Delta U_S$ increase with growth of thicknesses ratio $L_{LC}/L_D$ and with reduction of NLC dielectric anisotropy $\Delta\varepsilon$. The $-\Delta\delta/\Delta U_S$ values decrease at $U_{LC} = U_{th}$ and weakly rise at $U_{LC} = 2U_{th}$ with growth of elastic ratio $K_{33}/K_{11}$ [11]. We emphasize that effect of dielectric layers depresses the steepness of $\delta_0(U)$ curve at any bias voltage $U_{LC} \geq U_{th}$ (compare Fig. 3 and Fig. 6), i.e. decreases the optical response (contrast or difraction efficiency). To increase the response one has to diminish the thickness of dielectric layers ( e.g. use oxide films ) and the relative value of dielectric anisotropy $\Delta\varepsilon/\varepsilon_\perp$ (e.g. use substances with transverse dipole moment to increase $\varepsilon_\perp$), to select the optimal $K_{33}/K_{11}$ ratio. Some SLM designs with other controllable birefringence effects (twist-, supertwist-) are described in Refs. 17-19.

## 3. CONTROL OF SLM SWITCHING TIMES

For various problems of optical processing the switching time variation is required: increase of SLM speed of response (introducing of images) or receiving of optical memory (subtraction, storage of images).

When pulses of SLM driving voltage and writing light are synchronized, the SLM optical response increases 2-100 times in comparison with the case of fully dissynchronized pulses [20]. The maximal signal was observed at kilohertz frequencies.

In low frequency range ( tens of Hz ) the MDS-NLC structure has a linear electrooptical response to driving voltage. This is due to significant contribution of flexoeffect at these frequencies. We realized the optical subtraction using linear response and great value of switching time at $U_{LC} \to U_{th}$ [21].

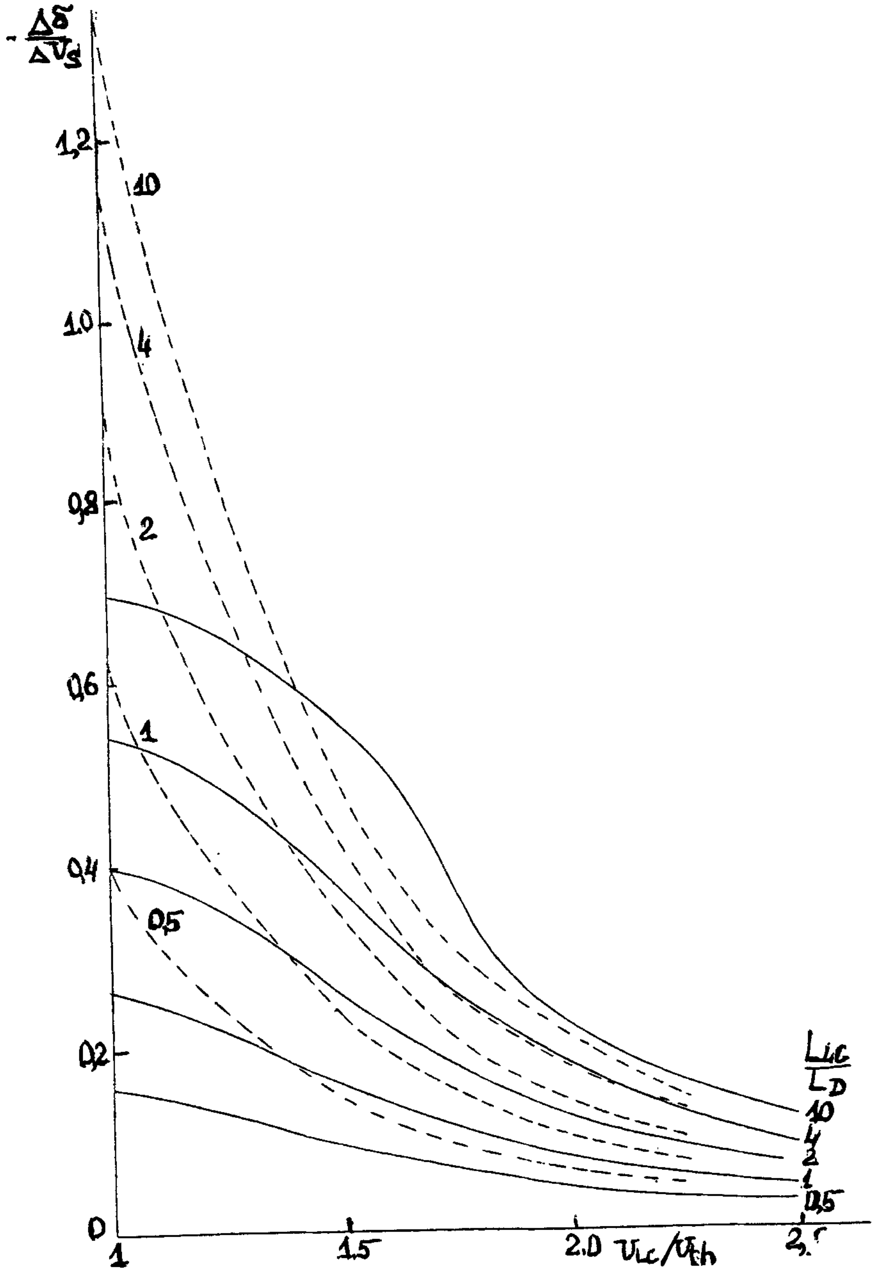


Fig. 6. The calculated relative optical response $\Delta\delta/\Delta U_S$ versus reduced bias voltage $U_{LC}/U_{th}$ at different $L_{LC}/L_D$ ratios and $\Delta\varepsilon$ =2 (---), 10.7 (---).

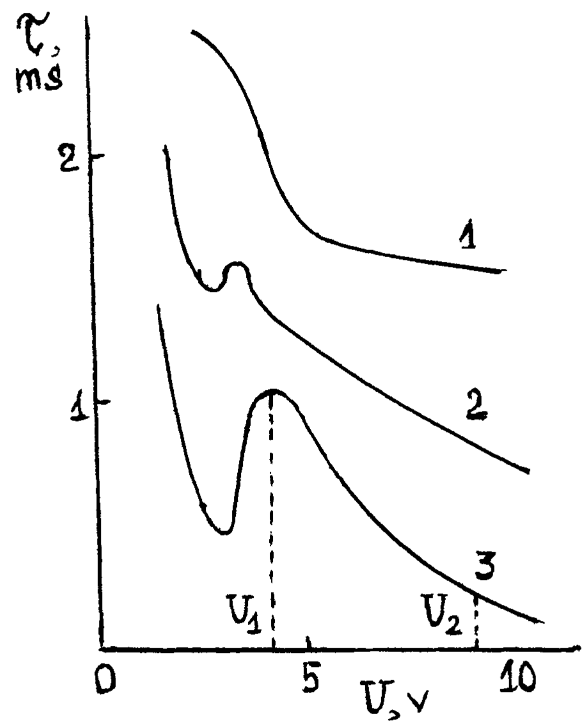


Fig. 7. The dependence of FLC switching time on driving voltage at different PVA concentrations C . C = 0.5 ( 1 ), 2 ( 2 ), 4 ( 3 ) 5 vol. PVA films are twice rubbed. $U_1$ and $U_2$ correspond bias voltages in dark and illuminated states of SLM input image .

The similar regime of forming of optical response was used in the amorphous silicon ( a-Si:H )-ferroelectric LC (FLC) SLM [22]. The relatively great difference of bias voltages $U_1$ and $U_2$ (Fig. 7) results in sufficiently high level of input intensity ( I ~ 0,1 mWt/sq. cm ) to obtain a full contrast (25:1) of transformed image. These high output image contrast ratios are observed up to 1 KHz frequency which is not optimal for MDS-structure. Because of that the resolution of SLM with FLC were low (~5 lp/mm). The achieved values of a contrast and a speed of response correspond to these ones obtained in [23-26] for ferroelectric Smectic C* LC and in [27] for antiferroelectric Smectic C* LC. The better speed of response (60 μs), resolution (250 lp/mm) and photosensibility (2-10 μWt/cm$^2$ ) for parallel information processing and projective systems were described in [28, 29].

The design of SLM for images storage and corresponding driving regime are described in Refs. 30, 31. The SLM is developed on the base of photoconductor-LC ( PC-LC ) structure with GaAs as a semiconductor and smectic A as a LC. The effect of confocal-homeotropic transition at f~5 KHz for writing of images and the effect of electrohydrodynamic instability at f~20-100 Hz for erasing of images are used in smectic A. The SLM driving is produced by short voltage pulses. The time of image writing is ca. 10 ms, erasing - ca. 100 ms, the storage time is unlimited. The images with resolution up to 20 lp/mm and contrast 40:1 were written in such SLM .

## 4. NON-LINEAR OPTO-OPTICAL MODULATION IN LC

The new generation of OA LC SLM may be developed on the base of various non-linear effects.

The fast optical response (several ms) in nematic 5CB on the xenon flash lamp pulses while applying a dc voltage was observed in [32]. The possible origin of that deep modulation (~90%) and store of written state during 500 ms is light scattering and the generation of an internal electric field.

The bistable dependence of transmitted light and polarization in dye-doped cholesterics (absorption spectrum corresponds helix pitch) was described in [33, 34].

The control of the electrooptic effect threshold voltage in antiferroelectric LC doped with photochromic dye by the cis-trans photoisomerization and then the possibility of spatial light modulation were proposed in [35].

The opto-optical SLM have simpler design than usual ones. The optical memory and logical functions may be realized.

## 5. CONCLUSION

New designs of OA SLM and optical systems based on SLM are worked out for solving of modern problems of optical processing: images entry in optical processor, subtraction, storage, dynamical selection of images and also the displaying of TV information onto great screen for group and collective use [36]. The concepts of significant improving of output image characteristics (brightness, contrast, grey scale, speed of response) or its spatial spectrum (resolution, difraction efficiency) are developed. The perspective possibilities of non-linear effects in LC are discussed.

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