LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

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Speckle suppression using a liquid-crystal cell

A.L. Andreev, I.N. Kompanets, M.V. Minchenko, E.P. Pozhidaev, T.B. Andreeva

***Abstract*. A simple method for suppressing speckles in images produced by laser projectors is proposed. The coherence of the laser beam and, therefore, speckles can be destroyed when the beam passes through an electrooptical cell in which a special ferroelectric liquid crystal is used as a modulating medium. The effect is achieved due to the spatially inhomogeneous phase modulation of light when specially shaped bipolar electric pulses are applied to the cell.**

Keywords: *speckles, liquid-crystal cell, phase modulation of light, scattering of light, speckle suppression.*

1. Introduction

Light-emitting diodes and lasers are promising light sources for small and bright projection displays. However, images in such systems suffer from the speckle noise arising, as strange it may sound, from a high quality of laser light, which, in this case, implies high coherence and monochromaticity of light [1 – 3]. The speckle pattern in images is the result of interference of many light waves scattered by different points of the screen, i.e. diffuser. The farther the observer from the screen and the smaller its size, the finer the speckle pattern. In practice, the speckle size is determined by the resolving power of the eye, which usually does not exceed one angular minute and lies in the range from 20 to 30 lines mm^{-1}. In addition, the response time of the eye ($\sim 1/25$ s) should be also taken into account in observations.

Speckles can be eliminated from images either by their averaging on a screen and or by destroying the phase relations in a laser beam, i.e. before projecting images on the screen.

The speckle averaging on a screen is achieved by using a fast moving (for example, fast rotating) light-scattering diffuser [4]. In the known holographic storage system [5], two diffusers moving with respect to each other were used to obtain more uniform holographic images. It is clear that mechanical movement is not the best solution of the problem.

A speckle-suppressing device (despeckler) destroying the coherence is a small and more efficient tool. Yet the device should have a rather high resolving power (of the order of hundreds or even thousands of lines mm^{-1}) due to the necessity of the following beam broadening with respect to the screen size as well should not decrease the laser beam intensity and deteriorate its directionality. A transparent phase mask with a random spatial phase distribution of the depth of the order π or more, which involves a fast-rotating bleached photoplate exposed through a diffuser (usually, a frosted glass plate) can serve as a despeckler [1, 2]. Mechanical movements can be avoided if the mask is realised by using a spatial phase light modulator, for example, a liquid-crystal modulator, which can generate Walsh or other orthogonal functions [6 – 8]. However, the use of such a multichannel phase modulator (in other words, an additional microdisplay) makes the optical system more complicated and expensive.

In this paper, a simple electrooptical cell (without light-modulation channels) filled with smectic ferroelectric liquid crystal (LC) is proposed as a spatial light modulator for speckle suppression. Applied to the cell, the electric field induces random variations in the refractive index across the cell. The phase of the passing light changes haphazardly by π or more. As a result, the laser beam becomes incoherent and unable to produce speckle patterns.

2. Experimental

The aim was to develop and investigate ferroelectric LC compositions and cells, which could suppress speckles. In addition, it was also necessary to find the conditions and electric-field control algorithm most suitable for fast generation of spatially inhomogeneous fine and random variations in the refractive index in the liquid-crystal layer.

To produce structures with a spatial inhomogeneity of the optical anisotropy, we used helix ferroelectric LC materials with electrically controlled birefringence and light scattering, which were developed at the P.N. Lebedev Physics Institute of the Russian Academy of Sciences [9 – 11]. The materials hold the ferroelectric phase over a wide temperature range and have a fast electrooptical response (less than a millisecond) – much shorter than the eyesight response time.

A.L. Andreev, I.N. Kompanets, M.V. Minchenko, E.P. Pozhidaev P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia;
e-mail: ALA-2012@yandex.ru, kompan@sci.lebedev.ru, mminchenko@mail.ru, epozhidaev@mail.ru;
T.B. Andreeva Business Invest Group Ltd., Bolshaya Cheremushkinskaya ul. 13/7, 117447 Moscow, Russia

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The particular property of all smectic liquid crystals is that the centres of mass of their molecules are periodically ordered along long axes (directors) of the molecules with the spacing of about a molecule length – the so-called smectic layers [12]. If the molecules are not mirror-symmetric (enantiomorphous) and there is an angle θ_0 between the director and the normal to smectic layers, then each layer has a single element of symmetry – the second-order polar axis. We can observe spontaneous polarisation $\boldsymbol{P}_s$ of the layer along that axis if molecules have a dipole moment directed perpendicularly to their long axes.

In the absence of external fields the polar axes of different smectic layers are located at an angle to one another so that the directors form a helix structure. In each layer the position of the director is defined by polar angle θ_0 and azimuth angle φ, the latter changing from 0 to 2π over the helix pitch p_0 (see Fig. 1).

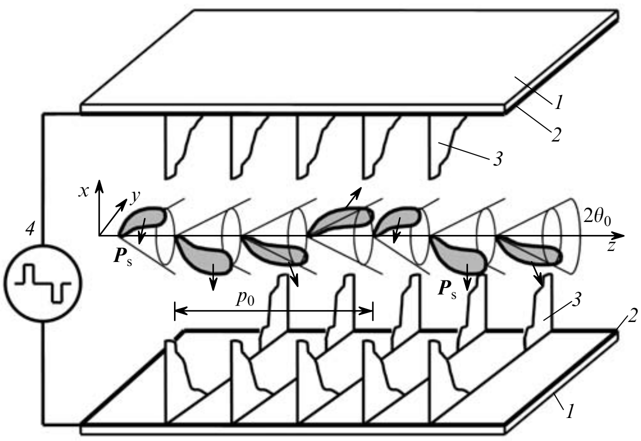


Figure 1. A helix ferroelectric LC in an electrooptical cell: (*1*) glass substrates; (*2*) transparent conducting coatings; (*3*) smectic layers; (*4*) control voltage generator.

If the applied electric field is parallel to smectic layers (along the x axis), the vector $\boldsymbol{P}_s$ is oriented in the direction of the field in all layers and causes the helix to unwind. When the sign of the electric field changes, the direction of the vector $\boldsymbol{P}_s$ changes to the opposite one. In this case, the long axes of the molecules describe a cone of aperture $2\theta_0$ with the azimuth angle of the director φ changing by 180°.

The change in the director orientation, which uniquely determines the principal axis of the refractive index ellipsoid of ferroelectric LC, results in changing the angle between the polarisation plane of the incident light (the light propagates along the x axis) and the principal axis of the ellipsoid. This means either modulation of the phase delay between the ordinary and extraordinary rays, or modulation of the light intensity (if the electrooptical cell is placed between the crossed polarisers).

If the width d of the electrooptical cell exceeds that of the pitch p_0 of the LC helix $d \gg p_0$ (in our case $d \approx 13 - 16$ μm, $p_0 \approx 0.5$ μm), the helix structure is not distorted without an external electric field, i.e. the helix pitch in the cell is equal to the equilibrium pitch p_0. If the external electric field $\boldsymbol{E}$ is applied perpendicular to the helix axis, the dipole moments of some LC molecules turn along the direction of $\boldsymbol{E}$ (which is the most advantageous orientation from the energetic point of view). The domain in which dipole moments are not aligned with the field is unstable, and regions appear [10] in which dipole moments are in the energetically advantageous position, namely in the smectic layers where the deviation of the azimuth angle φ from 0 or π had a maximum value at first.

This leads to the development of transient domains [10, 13] in which dipole moments of some molecules are directed opposite the field. These domains separate areas where the dipole moments and the electric field have the same direction. The transient domains represent bound states of two 180° walls of opposite signs. When the field amplitude reaches a critical value, the walls begin moving in the opposite directions according to their sign, so that the volume of energetically advantageous domain increases while the volume of energetically disadvantageous one decreases. As a result, the azimuth angle φ becomes the same and equal to 0 or π depending on the field direction in all smectic layers, and the vector $\boldsymbol{P}_s$ is oriented along the field. In this case, if directions of the polarisation plane of the incident light and the director of LC molecules (the principal optical axis) coincide, the light transmittance of the electro-optical cell has the maximum value.

The sign inversion of the electric field direction (the reversal of the polarity of the control voltage in other words) again induces the formation of transient domains, the movement of their domain boundaries and restoration of the original helix structure. In this case, the formation of transient domains causes variations in the refractive index along the helix axis and, as a result, intensive light scattering [10].

The efficiency of light scattering is usually determined by the contrast ratio S, i.e. the ratio of the intensity of the light traveling straight without scattering to that of the light scattered in some (small enough) solid angle. In our experiment the angle was set by a 1.5-mm septum placed 150 mm away behind the electrooptical cell output. The contrast ratio was measured with a 650-nm semiconductor laser whose beam was incident normal to the cell surface. A polariser was used to control the polarisation of the laser light.

The experimental setup included a light source (a 650-nm semiconductor laser), 2×2-cm ferroelectric LC cell, programmable electric-pulse generator, lenses, and a camera for photographing light-intensity patterns in the cross section of the laser beam propagated through the cell.

3. Experimental results and discussion

Random phase modulation of light across the beam in the electrooptical cell is a necessary condition for speckle suppression. An electric field of alternating direction is applied to the cell for a short period of time (~ 100 μs). It results in fine (of the order of micrometer and less) spatial deformations of the ferroelectric LC and corresponding haphazard variations in the refractive index in the volume of LC layer. These variations give rise to scattering of light at boundaries of transient domains in the helix structure of the ferroelectric LC. The degree of light scattering (contrast ratio) and transmittance of the electrooptical cell depend on the frequency or amplitude of the applied control voltage.

Variations in the refractive index may cause haphazard changes in the scattering indicatrix position if there are at least two light-scattering modes with different scattering mechanisms in the dependence of electrooptical response on

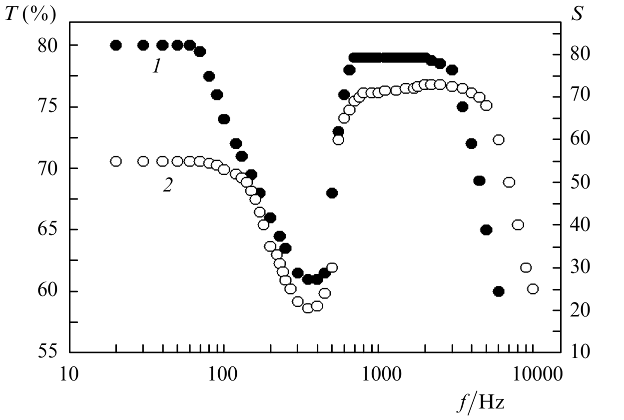


Figure 2. Frequency dependences of transmittance T (*1*) and light-scattering efficiency (contrast ratio *S*) (*2*). The control voltage is a meander of a ±36-V amplitude, the cell thickness is 13 μm.

the frequency or strength of the electric field. Experiments with a 13-μm-thick electrooptical ferroelectric LC cell with a 0.5-μm-pitch helix structure showed that two scattering modes exist depending on the electric-field frequency: low- and high-frequency modes, the scattering efficiency of the high-frequency mode being greater (Fig. 2).

In the low-frequency mode (the frequency of the control voltage is less than 200 Hz) the scattering starts at each alteration of the field direction, and the scattering efficiency does not depend on the field polarity (Fig. 3). In the high-frequency mode (the frequency is higher than 500 Hz) the period of scattering is half the time of the electric field action on the medium, and the scattering efficiency changes with the field polarity (Fig. 4).

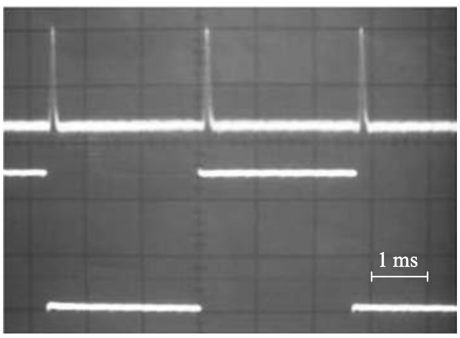


Figure 3. Oscillograms of the control voltage (bottom) and electrooptical response (top) in the low-frequency scattering mode. The low level of the electro-optical response corresponds to the maximum transmittance. The control voltage is a 150-Hz meander of a ±36-V amplitude, the cell thickness is 13 μm.

The transition from the low-frequency to high-frequency scattering mode leads to a considerable increase (up to 90°) in the angle between the polarisation plane of the incident light and the LC principal axis (the maximum of the scattering efficiency and transmittance is observed in the direction of this axis) (Fig. 5). This means that the scattering indicatrix turns through the angle of ~90° when the scattering modes are changed. Hence, when the high-frequency mode is activated, the character of LC director move during its reorientation changes. Because the director

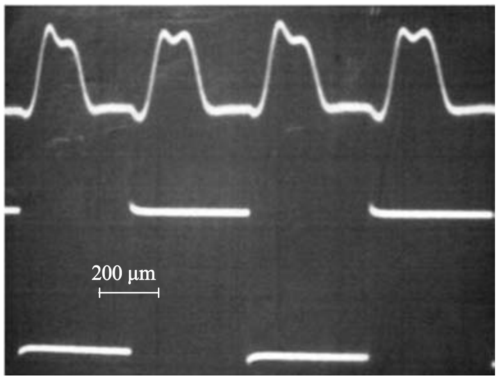


Figure 4. Oscillograms of the control voltage (bottom) and electrooptical response (top) in the high-frequency scattering mode. The control voltage is a 2-kHz meander of a ±36-V amplitude, the cell thickness is 13 μm.

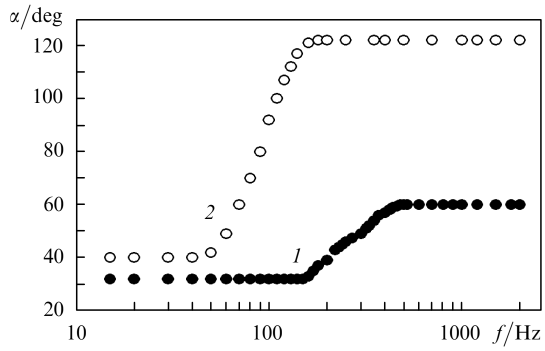


Figure 5. The angle between the light polarisation plane and the ferroelectric LC principal axis as a function of frequency at the maximum scattering efficiency. Curve (*1*) corresponds to electrooptical cells with a dielectric coating on a single substrate and curve (*2*) – to cells without a dielectric coating. The amplitude of the control voltage (meander) is ±36 V. The cell thickness is 13 μm.

in our case is reoriented by moving domain boundaries, the velocity of this moving should also be dependent on the electric-field frequency.

If the form of the moving 180° domain wall does not differ from its initial static form, and the speed of this moving is constant (steady motion), the effective mass of the wall can be ignored in the equation of motion. In this case, the equation of the director motion along the z axis (Fig. 1) can be written in the form [13]

$$\gamma_\varphi \frac{\partial \varphi}{\partial t} = K_\varphi \frac{\partial^2 \varphi}{\partial z^2} \pm |\boldsymbol{P}_\mathrm{s}||\boldsymbol{E}| \sin\varphi + \frac{2W_\mathrm{q}}{d}\sin 2\varphi + \frac{W_\mathrm{p}}{d}\sin\varphi, \quad (1)$$

where $K_\varphi(\partial^2\varphi/\partial z^2)$ and $\gamma_\varphi(\partial\varphi/\partial t)$ are the elastic and viscous moments; γ_φ is the rotation viscosity coefficient; K_φ is the modulus of elasticity which defines the azimuth-angle deformation of the director φ; $|\boldsymbol{P}_\mathrm{s}||\boldsymbol{E}|\sin\varphi$ is the moment of forces acting on the director in the electric field; W_q is the quadratic coefficient of the anchoring energy, i.e. the energy needed to deflect the director from the equilibrium (energetically most advantageous) position; W_p is the difference between the polar coefficients of the anchoring energy on the top and bottom substrates. The electric field is switched on at time $t = 0$.

The polar boundary conditions ($W_\mathrm{p} \neq 0$) suggest that the angles between the vector $\boldsymbol{P}_\mathrm{s}$ and the normal to the surface on the top and bottom substrates are different. The polar part of the anchoring energy (noncompensated surface charge) causes polarisation of the ferroelectric LC in the absence of the electric field.

Equation (1) has an exact solution if the domain wall is treated as a topological soliton and by assuming that the ferroelectric LC structure is in basic, but different states at $z = \mp\infty$: $\varphi(z = -\infty) = 0$ and $\varphi(z = +\infty) = \pi$. The solution of (1) describes the soliton motion along the z coordinate with the velocity

$$\upsilon = \left(\frac{K_\varphi d}{2W_{\rm q}}\right)^{1/2} \frac{P_{\rm s}Ed + W_{\rm p}}{\gamma_\varphi d}. \quad (2)$$

In weak fields the velocity υ of the wall motion, which is inversely proportional to the inverse electrooptical response time $1/\tau_{0.1-0.9}$, depends linearly on the field strength E (Fig. 6). This corresponds to the deformation-free translation of the domain wall [expression (2)]. When the electric-field frequency increases, the quantity $1/\tau_{0.1-0.9}$ increases drastically (and the velocity υ as well) and rapidly saturates [Fig. 6, curve (*2*)]. It means that a high-frequency field induces bending vibrations in a domain wall. This results in an increase in the electric moment in the direction of motion and, therefore, the velocity of the wall motion. A change in the structure determines the inertial properties of the domain wall (i.e. its effective mass) when the motion is not steady.

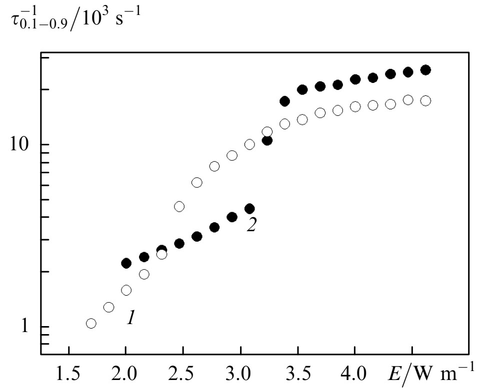


Figure 6. Inverse time of the electrooptical response versus the field strength E for the frequency of the control voltage (meander) 100 Hz (*1*) and 1 kHz (*2*). The cell thickness is 13 μm, the substrates have no dielectric coatings.

Dielectric screening of one of the substrates of the electrooptical cell (polar, i.e. asymmetric boundary conditions with $W_{\rm p} \neq 0$) causes polarisation of the ferroelectric LC. The consequence is deformation (fractional unwinding) of the helix and formation of transient domains in the absence of the electric field. As a result, the angle of the scattering indicatrix turning decreases to 30° [Fig. 5, curve (*1*)] upon the transition to the high-frequency scattering mode. In addition, under asymmetric boundary conditions the electrooptic response time falls by a factor of 1.5–2. This is due to the increase in the motion velocity of domain boundaries, which is proportional to the coefficient $W_{\rm p}$ [expression (2)].

A simultaneous action of low- and high-frequency electric fields (whose relative amplitudes depend on such ferroelectric LC parameters as the helix pitch, rotation viscosity, spontaneous polarisation, helix elasticity energy, as well as on the boundary conditions and the cell thickness) on the electrooptical cell causes the chaotic modulation of the scattering indicatrix direction due to random variations in the refractive index in the LC layer. The result is the random spatially inhomogeneous phase modulation of laser light (Fig. 7). The averaged electrooptical response of the cell measured behind the crossed polarisers (the upper oscillogram in Fig. 7) characterises this kind of modulation. One can see that the phase shifts are random both in time and space. The number of deep minima in the electrooptical response curve along the half-period of the meander corresponds to the number of π-shifts in the phase delay modulation over the time of that half-period. For example, this number is equal to four for the third half-period of the meander.

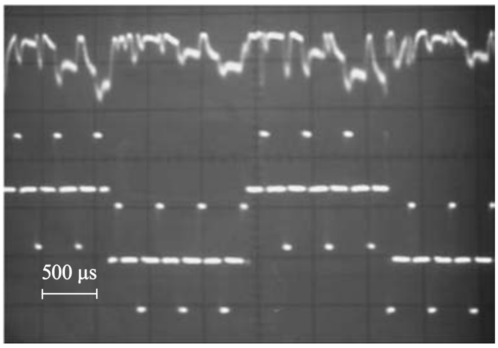


Figure 7. The oscillograms of the control voltage applied to the16-μm-thick electrooptical cell. The low-frequency signal (meander) has the frequency of 450 Hz and the amplitude of ±30 V. The modulating signal (pulses of alternating polarity) has the frequency of 3.5 kHz and the amplitude of ±20 V. The upper curve is the electrooptical response (phase delay modulation).

For a given light wavelength the phase modulation depth M is defined by the birefringence coefficient Δn of the ferroelectric LC and the electrooptic cell thickness d, and depends on the amplitude of the control voltage. One can see from Fig. 8 that for a 16-mm-thick cell the maximum modulation depth (4π) is achieved for a ±20 V amplitude of the electric signal.

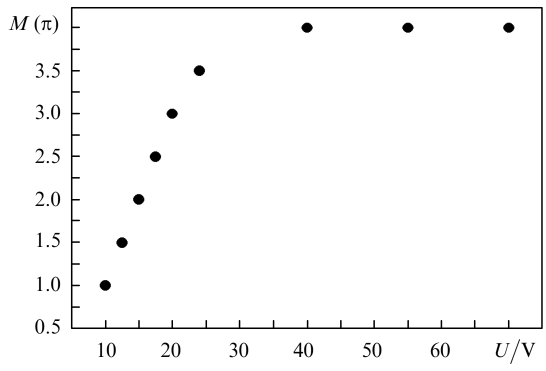
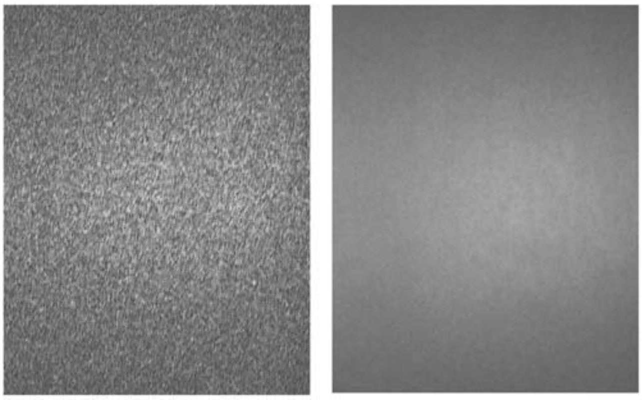


Figure 8. The phase-delay modulation depth M as a function of the amplitude U of the control voltage (meander). The thickness of the electrooptical cell is 16 μm, and the laser wavelength is 650 nm.



a b

Figure 9. Cross-sectional images of a laser beam behind the electrooptical cell with the control voltage switched off (a) and on (b). The thickness of the ferroelectric LC layer is 16 μm, the wavelength is 650 nm, the low-frequency signal (meander) has the frequency of 450 Hz and the amplitude of ±30 V, the modulating signal (pulses of alternating polarity) has the frequency of 3.5 kHz and the amplitude of ±20 V.

Thus, for the given parameters of the control voltage we can observe both the randomly changing direction of the principal optical axis of the ferroelectric LC (scattering indicatrix) and the random phase shifts (up to 4π) of the passing light. The result is the fast space and time phase modulation of light which allows suppression of speckle patterns. The effect of the suppression is shown in Fig. 9b. Here, the efficiency of speckle suppression in the laser beam cross section is 50 %.

4. Conclusions

We have shown experimentally for the first time that it is possible to destroy the coherence of a laser beam and suppress speckle patterns in real time using a single liquid crystal cell in which an alternating electric field generates fine structures with random variations in the refractive index over the entire LC layer.

Conditions have been considered which provide arising small-scale haphazard spatial deformations in the ferroelectric LC layer resulting in refractive index variations and short-time switching on of light scattering. The parameters of the alternating control electric field ensuring these conditions have been also determined. A simultaneous action of low- and high-frequency control voltages makes the LC scattering indicatrix change chaotically, ensuring conditions for a spatially inhomogeneous and random phase modulation of the light passing through the cell. Recall that short (no longer than 100 μs) switching on of light scattering is not sensitive for eyes and does not affect the perception of images.

The choice of the appropriate ferroelectric LC composition, the manufacturing technology of the electrooptical cells and two-frequency electric control provides 50 % efficiency of speckle suppression, which is a notable achievement for today.

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