Speckle-noise suppression using electro-optical cell with helix-free ferroelectric LC

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Abstract. The authors develop an original and promising method of suppressing the speckle-noise in images generated by a laser beam by means of a compact despeckler based on an electro-optical cell with the smectic ferroelectric liquid crystal (FLC), realizing spatially inhomogeneous phase modulation of light. The mechanisms of destruction of the phase relations in the laser beam passing through a cell with helix-free FLC are discussed. The electric field induces the light scattering and small-scale randomly distributed gradients of the refractive index in FLC layer. The features and benefits of a despeckler using helix-free FLC compared to helix FLC are indicated.

1. Introduction

In works [1, 2] a method of spatially inhomogeneous light phase modulation using a simple electro-optical cell filled with liquid crystal (LC), namely ferroelectric LC (FLC) of the smectic type with a helix structure was proposed. The alternating electric field of the order of 2 V/µm applied simultaneously at a low frequency (450 Hz) and high frequency (3500 Hz) caused the spatial deformations of a helix and resulted in the formation in LC layer of about 18 µm thickness the small-scale spatially inhomogeneous and quickly changeable structures with random distribution of the refractive index gradients. As a result, caused by the alternating field action the spatially inhomogeneous phase modulation of the light passing through a cell was realized in FLC layer due to chaotic changes of the position of the scattering indicatrix, and modulation depth was of the order and more than π, and moreover the high spatial resolution was achieved (order of the helix pitch, i.e. fractions of a micrometer). This allowed to destroy the phase relationships in the laser beam and its ability to interference, and, consequently, to suppress the speckle-noise in images generated by a laser.

In [3-5] the optical modulator - despeckler based on an electro-optical cell with helix-free FLC was described. Helical twisting of the director in a layer of this FLC was compensated due to the interaction of chiral additives with opposite signs of optical activity. The effect of the spatially inhomogeneous (over the aperture) phase light modulation in FLC layer was achieved by simultaneous action of the high-frequency (10 kHz) and low frequency (1000 Hz) voltage pulses, i.e. the interval of light modulation frequencies at the electric field of the order of 2 V/µm was increased twice in comparison with [1], that increases the possible applications of the modulator. Its main advantages are the absence of distortions in the spectral composition of the modulated optical radiation and the lack of...
light scattering when you turn off the electric field. In addition, the same shape (square wave) of voltage pulses on the low and high frequencies allowed simplifying the electronic control circuit.

Below we discuss the mechanism and parameters of spatially inhomogeneous phase light modulation in the helix-free FLC- materials (in comparison with helix materials) and the prospects for the practical use of the method in laser display devices.

2. The mechanism of light scattering and spatially inhomogeneous phase modulation in helix FLC
Spatially inhomogeneous phase modulation is a consequence of chaotic change of the position of FLC scattering indicatrix, when the control voltage pulses of low and high frequency simultaneously are applied to an electro-optical cell.

In our previous works [6, 7] the light scattering on the dynamic domain structure arising in the nonlinear process of reorientation of the helix FLC director in an alternating electric field was described. Scattering was characterized by high speed (switching on and off times of the scattering process do not exceed 150 µs at the field tension of 5 V/µm) and good efficiency - contrast ratio was about 100: 1 or higher.

It should be noted that the deformed helix FLC structure changes the spectral composition of light. Moreover, after electric field switching off the residual light scattering occurs due to the helix. Besides, when the electric field strength is lower than 3 V/µm the frequency of light modulation in an electro-optical cell at the regime of spatially inhomogeneous phase modulation is limited (less than 500 Hz) that reduces the possible applications of a despeckler.

3. The mechanism of light scattering in helix-free FLC
Below we consider a new type of light-scattering FLC materials. These materials - specially designed helix-free FLC, capable to operate effectively in the regime of electrically controlled light scattering.

In an electro-optical cell with helix-free FLC in the absence of an electric field at a certain ratio between FLC rotational viscosity γϕ, spontaneous polarization Ps and modulus of elasticity determining the deformation along smectic layers Kϕ, when Ps < 50 nC / cm², K = (1+3)·10^{12} N and 0.3 < γϕ < 1.0 Poise, the periodic deformation of smectic layers arise, resulting in periodic changes in the position of FLC director along each layer [9]. Smectic layers are treated as periodic ordering of the centers of molecule mass in the direction of the director with a period of the order of FLC molecule length.

In the work we used helix-free FLC with the following parameters: Ps = 40 nC / cm², γϕ = 0.7 Poise, tilt angle of the molecules in smectic layers Θ₀ = 23° (at 20 °C) and temperature range of the existence of the ferroelectric (chiral smectic C*) phase from 2 °C to 70 °C.

The alternating electric field applied along the smectic layers, interacting with the spontaneous polarization changes the distribution of the director in each smectic layer. The development of this process, due to the transition to the Maxwell mechanism of energy dissipation, causes the appearance of a soliton, which is the wave packet with a periodic wave localized in it (soliton train) [3, 9].

The appearance of waves with a stationary profile results in the formation of the structure of transient domains - spontaneously ordered regions, where light scattering occurs on the borders. Movement of solitons reorients the director in all volume of FLC layer. In this case, if the polarization plane of the incident light is along the direction of FLC director (along the main optical axis), the light transmittance of an electro-optical cell is maximum. Invert the sign of the electric field (the polarity of a control voltage pulse) induces the formation of new soliton wave that causes the appearance of refractive index gradients along smectic layers and accompanied with intensive light scattering.

Under certain conditions, the scattering process can have a bistable character (Figure 1).

There is an optimal ratio between the period of deformation of smectic layers and the thickness of an electro-optical cell, when at a certain electric field tension the velocity of soliton waves motion is maximum (the electro-optical response time is minimum correspondently), and the light modulation frequency is maximum also.
For used FLC with the deformation period of about 2 µm the optimal thickness of an electro-optical cell is of about 20 µm. For the concrete cell with FLC thickness of 18 µm the maximum light modulation frequency is about 5 kHz (time $\tau_{0.1-0.9}$ does not exceed 12 µs) at the electric field strength of 2.7 V / µm (Figure 1).

Switching by bipolar voltage pulses provides the operation of an electro-optical cell in bistable mode with light transmission of about 80% and a contrast ratio of over 200:1. However, unlike the helix FLC, both optical states in a cell with helix-free FLC can be memorized for several tens of seconds after switching off an electric field or until the arrival of a pulse of the opposite polarity [3].

4. The deformation of smectic layers

The presence of periodical deformations of smectic layers means that FLC molecules initially inclined by the angle $\Theta_0$, relative to the normal to a layer at some point, are deflected additionally by the angle $\psi$ with respect to z-axis (Figure 2). Because of this the projection of the director on the $xy$ plane changes. The thickness of the curved smectic layer in the projection on the axis z: $l = l_0 \cos \Theta_0 / \cos \psi$.

Reorientation of FLC director due to the interaction of the alternating electric field $E$ (the field is applied along the coordinate y) with the spontaneous polarization $P_S$ can occur both at changing the azimuth angle $\varphi$ of the director orientation by $180^\circ$, when the director is reoriented along a cone surface with the cone angle $2\Theta_0$, and at changing the distribution of the angle $\psi$, describing the deformation of smectic layers. In the first case the dissipative coefficient is a rotational viscosity $\gamma_\varphi$, while in the second case - the viscosity $\gamma_\psi$ at the shear deformation [10].
If the frequency of changing the external electric field $f \sim 1/\tau_m$ (here $\tau_m$ - Maxwellian relaxation time, i.e. the time during which a shear tension after deformation caused by the electric field returns to the unperturbed state), the viscosity is defined by the shear modulus $\mu$ [11]: $\gamma \sim \tau_m/\mu$.

Otherwise, if the time $\tau_m$ is frequency independent, the viscosity $\gamma_\nu$ also does not depend on the frequency. In this case the director reorientation time $\tau_R \sim \gamma_\nu/P_S E$ [12]. Accordingly, if $\tau_m$ varies with the frequency, the viscosity of the molecular system will change with regarding to the variation of frequency as well. As a result, the dissipative coefficient is $\gamma_\nu$ – the viscosity at the shear deformation.

The character of the process of FLC director reorientation under the influence of the alternating electric field depends on which of two dissipative coefficients (rotational or shear viscosity) predominates. The transition to Maxwellian mechanism of energy dissipation (when the shear viscosity $\gamma_\nu$ becomes the dissipative coefficient) results in the appearance of a soliton, which is a localized wave packet with the periodic wave in it [3].

The maximal speed of the soliton motion can be written as:

$$V = 2\Theta_0 \sqrt{\alpha K/\gamma_\nu d} = (\Theta_0/\gamma_\nu) \sqrt{2K(M + P_S E \cos \varphi_0)}.$$  \hspace{1cm} (1)

Characteristic time of the director reorientation due to the movement of the orientation bend is as follows [3]:

$$\tau_C = \frac{\gamma_\nu d^2}{K \xi} = \frac{2\gamma_\nu}{\Theta_0^3 (P_S E \cos \varphi_0 + M)} \hspace{1cm} (2)$$

At the initial azimuth angle of the director orientation $\varphi_0 = 30^\circ$, the spontaneous polarization $P_S = 50$ nC/cm$^2$, the energy of smectic layers deformation $M = 4 \cdot 10^3$ erg/cm$^3$, elasticity coefficient $K = 5 \cdot 10^{12}$ N, the electric field $E = 3$ V/µm, the molecules tilt angle in smectic layers $\Theta_0 = 23^\circ$ and $\gamma_\nu = 0.2$ Poise the velocity of the soliton center of $V = 0.65$ cm/s, and the time of the director reorientation is $\tau_C \approx 150$ µs [3].

5. Spatially inhomogeneous light scattering structures in helix-free FLC

The transition to Maxwellian mechanism of energy dissipation is accompanied with a strong frequency dependence of the time $\tau_{0.1-0.9}$ (Figure 3, curve 1). Increasing this time on the first stage (not more than 25%) is due to the presence of both dissipative coefficients $\gamma_\nu$ and $\gamma_\nu$, and probably the value of shear viscosity $\gamma_\nu$ in this case does not exceed 0.2 Poise (for used FLC with $\gamma_\nu = 0.7$ Poise). When shear viscosity begins to predominate the time $\tau_{0.1-0.9}$ decreases a few times. At farther frequency increasing, when the transition to the soliton mode takes place, the optical response time is defined by the velocity (1) of soliton waves motion, and the frequency dependence of $\tau_{0.1-0.9}$ practically disappears.

The transition to Maxwellian mechanism of energy dissipation is accompanied also with diminishing the birefringence index $\Delta n$ (Figure 3, curve 2). The maximum change $\Delta n$ (about one and half times) takes place at the transition to the soliton mode.

Light scattering in helix-free FLC is due to the spatial inhomogeneity of the optical anisotropy: scattering occurs on the boundaries of spontaneously ordered regions, which are formed in FLC, when waves of a stationary profile – solitons appear. This results in forming a structure of transient domains (scattering centers), when inhomogeneous distribution of electric polarization appears along the direction of smectic layers. The action of the high-frequency electric field increases the length of domain boundaries and forms a sufficiently regular structure of circular domains that in turn results in an increasing the density of scattering centers. Changing the direction of the electric field induces the formation of a new domain structure that causes the appearance of refractive index gradients along smectic layers, and this process is accompanies again with intense light scattering.

When operating in light scattering mode the polarizers are not required, that increases the transmission of an electro-optical cells up to 80%. This transmission is limited mainly by the light transmission of transparent conductive coatings deposited on glass substrates. To estimate the efficiency of scattering the contrast ratio is commonly used, which is defined as the ratio of intensities
of light radiation propagating in a straight direction without scattering and scattering in a sufficiently small solid angle.

Figure 3. Frequency dependence of the electro-optical response (1) and the index of birefringence $\Delta n$ (2). The thickness of an electro-optical cell $d = 13 \, \mu m$. The electric field $E = 6 \, V / \mu m$. Bipolar control voltage is of the rectangular shape (meander), amplitude is $\pm 35 \, V$.

The efficiency of the light scattering and light transmission of an electro-optical cell is defined by the frequency and amplitude of the control voltage. At a fixed electric field tension (amplitude of bipolar pulses of the control voltage), the maximum efficiency of light scattering (i.e. contrast ratio) and the maximum light transmission of an electro-optical cell are achieved at different pulse duration (Figure 4). This means that the time of forming a regular structure of transient domains and the time of complete disappearance of this structure differ. So, for switching to a state with maximum light transmission, which corresponds to the complete absence of transient domains, the pulses of $1.5 \div 2$ times larger duration are required (Figure 4, curve 2). If the pulse duration is less than the minimum time required for complete disappearance of transient domains, then the light transmittance of a cell decreases.

Figure 4. The dependence of the light scattering efficiency (curve 1) and light transmission (curve 2) on the duration of bipolar voltage pulses at the fixed amplitude. The amplitude of pulses is $\pm 35 \, V$. The thickness of an electro-optical cell is $13 \, \mu m$.

At the inversion of electric field sign (i.e. pulse polarity) not enough time of field action (i.e. small pulse duration) does not allow forming a regular structure of transient domains that results in decreasing the density of scattering centers, and as a consequence the efficiency of light scattering decreases. Namely, a regular structure of circular domains as scattering centers fairly uniformly distributed throughout the volume of FLC layer corresponds to the maximum efficiency of light scattering. The dependence of the scattering efficiency – contrast ratio on voltage pulse duration and thickness of an electro-optical cell can show a few maximums of the scattering efficiency (Figure 5). The appearance of the second and third maximums of the scattering efficiency occurs at increasing the thickness of an electro-optical cell (compare Figure 4 and Figure 5).

Increasing the pulse duration results in increasing the length of domain boundaries and the transition to irregular scattering structures. Because of this, the density of scattering centers reduces that in turn results in decreasing the scattering efficiency.
The transitions between the light-scattering modes (maximums of the light scattering efficiency correspond to them), while feeding voltage pulses with the duration corresponding to different maximums, result in the chaotic change in the position of the scattering indicatrix. As a result of short-term (less than 50 µs) switch on, light scattering in FLC the structures are formed with a random distribution of the refractive index gradients over the volume of FLC layer that in turn causes the spatially inhomogeneous (in the cross-section of the light beam) phase modulation of light in an electro-optical cell.

Thus, chaotic light scattering in helix-free FLC layer is the result of the appearance of refractive index gradients at the inversion of electric field sign (polarity of control voltage pulses), and the reason of this is nonlinear mechanism of FLC director reorientation due to soliton waves motion.

Figure 5. The dependence of the light scattering efficiency on the duration of bipolar voltage pulses at a fixed amplitude. The amplitude of pulses is of ± 50 V. The thickness of an electro-optical cell is 18 µm.

6. Spatially inhomogeneous light modulation and speckle-noise suppression

Spatially inhomogeneous modulation of a phase delay, the depth of which is of the order and more than π allows to destroy phase relationships in a laser beam passing through an electro-optical cell, and, as a consequence, to suppress the speckle-noise in images [4].

Phase light modulation with a high level of inhomogeneity is reached at the amplitude modulation of bipolar voltage pulses of the rectangular shape (meander) and frequency of 1 kHz by high-frequency voltage (10 kHz) of the same shape at the electric field tension of the order of 2 V/µm (Figure 6). The amplitude, duration and pulse repetition frequency are selected so that the light scattering efficiency changes for the duration of each pulse of pulse sequence, but it does not reach its maximum value. The consequence of the selected voltage regime is the spatially inhomogeneous light phase modulation with the depth of up to 4π that destroys phase relations in a laser beam passing through FLC cell and suppresses the speckle-noise in images.

Figure 7 shows the photo of intensity distribution - speckle patterns (a) in the cross section of the laser beam behind FLC electro-optical cell and its measured profile along the indicated line (b) in the absence of the control voltage. Figure 8 shows the photo of intensity distribution (a) and its measured profile (b) when the control voltage is applied to FLC electro-optical cell. One can see that speckle noise in Figure 11 is suppressed significantly. The level of suppression of speckle noise in Figure 8 can be estimated from the measured value of the contrast function C [13], which is defined as the ratio of the standard deviation \( \sigma \) of intensity fluctuations to the average value of the intensity \( <I> \):

\[
C = \frac{\sigma}{<I_k>} = \sqrt{\frac{\sum_{m=1}^{M} \sum_{n=1}^{N} I_k^2}{<I_k>^2} - \frac{1}{M \cdot N} \sum_{m=1}^{M} \sum_{n=1}^{N} I_k^2} = \frac{1}{M \cdot N} \sum_{m=1}^{M} \sum_{n=1}^{N} I_k^2
\]

where \( M \) - the width of the speckle pattern in pixels, \( N \) - the height of speckle pattern in pixels, \( I_k \) - intensity value in frame point k with coordinates \( \{m, n\} \).
Figure 6. Waveforms of the control voltage (channel CH3) applied to FLC electro-optical cell of 18 µm thickness, and the optical response - modulation of the phase delay (channel CH1). The low-frequency signal (meander) – 1 kHz, amplitude ± 35 V. The high-frequency signal (meander) – 10 kHz, amplitude ± 35 V.

Figure 7. Photo of the intensity distribution in the cross-section of a laser beam passing through FLC cell in the absence of a control voltage (a) and the corresponding intensity profile along the indicated line in the dependence on a number of analyzed pixels (b), like in Figure 7 (a). The laser wavelength - 0.65 µm; FLC layer thickness - 18 µm.
The theoretical value of the speckle-pattern contrast varies in the range from 0 to 1. The maximal possible contrast value \( C = 1 \) can be achieved only in a fully developed speckle-fields observed at the diffraction of broad laser beams on strongly rough surface or strongly scattering random transparency [14].

The effectiveness of reducing the speckle contrast was calculated as the ratio \( R \ [dB] \) between the contrast \( C_1 \) observed at switched off voltage and the contrast \( C_2 \) observed at switched on control voltage, namely [14, 15]:

\[
R = 10 \ln \left( \frac{C_1}{C_2} \right).
\]

(4)

The contrast of the speckle pattern, shown in Figure 7 (a) was 0.72. The contrast of the speckle pattern, shown in Figure 8 (a) - 0.21. According to measurement data, the contrast decreased more than 3 times, and the effectiveness of reducing the contrast of presented speckle patterns is 5.4 dB. This result corresponds to theoretical concept and it is quite good.

Figure 8. Photo of the intensity distribution in the cross-section of a laser beam passing through FLC cell upon application of a control voltage (a) and the corresponding intensity profile along the indicated line in the dependence on a number of analyzed pixels (b), like in Figure 8 (a). The laser wavelength - 0.65 µm; FLC layer thickness - 18 µm.
7. Conclusion
Electrically controlled spatially inhomogeneous phase modulation of light in the helix-free FLC allowed to realize the effective suppression of the speckle-noise at the electric field tension of about 2 V/\mu m and frequency of about 2 kHz. Experiments showed that a despeckler based on an electro-optical cell with helix-free FLC has advantages over a despeckler using helix FLC.

The modulation frequency in helix-free FLC is four times higher than in helix FLC, and the shape of low-frequency and high-frequency signals is the same that simplifies a control scheme. Since a helix is absent, there are no distortions in the spectral composition of modulated radiation and no light scattering in the absence of the electric field. Spontaneous polarization of used helix-free FLC is less than 50 nC/ cm\(^2\), therefore there are no diffraction and light scattering due to ferroelectric domains (at electric field switching off), which appear at the spontaneous polarization more than 70 nC/ cm\(^2\).

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