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Research of light diffraction on electrically controlled multilayer inhomogeneous PPM-LC structures with smooth optical inhomogeneity

In this work a theoretical model of light diffraction on electrically controlled multilayer inhomogeneous holographic diffraction structures formed in a photopolymer material with a high proportion of nematic liquid crystals is presented and numerical calculation of diffraction characteristics for such structures are performed. The received results can serve as a basis for further development of electrically controlled spectral filters.

INTRODUCTION

Nowadays, more and more attention of many researchers is attracted by multilayer inhomogeneous holographic diffraction structures (MIHDS), which can potentially be applied as elements of spectral filters, as well as for formation of a sequence of ultrashort laser pulses. A feature of these structures is their angular selectivity, which is a set of local maxima, the number and width of which depend on the ratio of the thickness of the buffer and diffraction layers.

Earlier in [1], the possibility of controlling the diffraction characteristics of such structures using an external electric field was demonstrated. The control was achieved due to the presence of nematic liquid crystals (LC) in a composition with a photopolymer material in each diffraction layer of a multilayer structure. LCs are sensitive to electrical action and can change their orientation under its influence, which eventually leads to a change in wave propagation in the medium [2].

However, in [1], the case was considered when diffraction layers contain polymer encapsulated liquid crystals, and when such structures are formed, complete phase separation occurs, which causes optical uniformity in depth. When the LC content in the composition with PPM is more than 90 percent, the medium has a smooth optical inhomogeneity, which must be taken into account when solving the diffraction problem.

Thus, the aim of this research is to study the diffraction of light on electrically controlled MIHDS with PPM-LC having smooth optical inhomogeneity.

THEORETICAL MODEL OF LIGHT DIFFRACTION ON MIHDS WITH PPM-LC

At a high concentration of LC molecules during the formation of holographic diffraction structures (HDS), their orientation is determined by the boundaries of the sample and is described by the Fredericks equation [4]:

$$\frac{1}{\xi_E(E)}\left(\frac{d_n}{2}+y\right)=\int_0^{\varphi(\mathbf{r},E)}\left(\sin^2\varphi_m(\mathbf{r},E)-\sin^2\varphi\right)^{-1/2}d\varphi$$

where $\varphi_m(\mathbf{r},E)$ and $\varphi(\mathbf{r},E)$ is the maximum angle and angle of rotation of the LC director from the y axis (according to the depth of the layer with HDS), $\xi_E(E)=\sqrt{(4\pi K)/(E^2\Delta\varepsilon)}$ is the electrical coherent length, K is the elasticity coefficient of the LC, d_n is the thickness of the diffraction layer, n is the layer number.

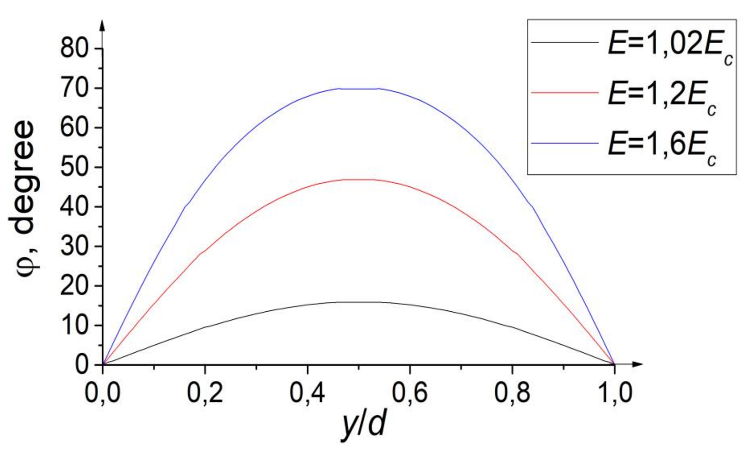

Fig. 1. Dependence of the rotation angle of the LC director on the voltage of the electric field along the thickness of the PPM-LC layer

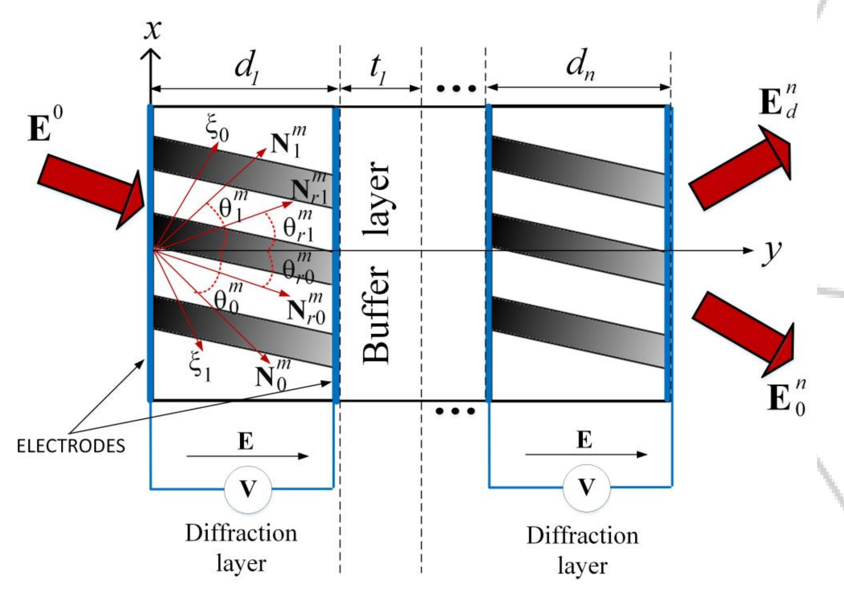

Fig 2. Scheme of light diffraction on MIHDS in PPM-LC

The amplitudes of interacting waves in the case of Bragg diffraction are determined by systems of coupled wave equations (CWE) in partial derivatives [4]:

$$\mathbf{N}_{r0}^{m,n}\cdot\nabla E_0^{m,n}=-iC_1^{m,n}\cdot n_1^{m,n}\cdot E_1^{m,n}\cdot\exp\left[+i\Theta_n^m\right],$$

$$\mathbf{N}_{r1}^{m,n}\cdot\nabla E_1^{m,n}=-iC_0^{m,n}\cdot n_1^{m,n}\cdot E_0^{m,n}\cdot\exp\left[-i\Theta_n^m\right],$$

where $C_j^{m,n}(E)$ are coupling coefficients; *j*=0.1; $n_1^{m,n}(\mathbf{r})$ is the refractive index of the first harmonic; *m*=*o*,*e*; $\Theta_n^m(\mathbf{r})=\Delta K^{m,n\prime}y+t_y^n y^2/2$ is the integral phase mismatch; $\Delta K^{m,n\prime}$ is the component of the vector $\Delta\mathbf{K}^{m,n}(\mathbf{r})$ at $\mathbf{r}$=0, and t_y^n is defined as [4]:

$$t_y^n=k_0^{e,n}\Big[\left(\mathbf{y}_0\cdot\mathbf{N}_0^{e,n}\right)\left(\mathbf{y}_0\cdot\nabla n_0^{e,n}\right)-\left(\mathbf{y}_0\cdot\mathbf{N}_1^{e,n}\right)\left(\mathbf{y}_0\cdot\nabla n_1^{e,n}\right)+$$
$$+\frac{\left(\mathbf{y}_0\cdot\mathbf{m}_0^{e,n}\right)\left(\mathbf{m}_0^{e,n}\cdot\nabla n_0^{e,n}\right)}{\left(\mathbf{N}_{r0}^{e,n}\cdot\mathbf{y}_0\right)}-\frac{\left(\mathbf{y}_0\cdot\nabla n_1^{e,n}\right)\left(\mathbf{m}_1^{e,n}\cdot\nabla n_1^{e,n}\right)}{\left(\mathbf{N}_{r1}^{e,n}\cdot\mathbf{y}_0\right)}\Big],$$

where $\mathbf{m}_j^{e,n}$ is the basic orthograph of the hodograph; $\nabla n_{0,1}^{e,n}$ is the changes in the refractive index.

To solve the CWE in partial derivatives, it is necessary to approximate the parameter of the integral phase mismatch $\Theta_n^m(\mathbf{r})$ for each MIHDS layer with an PPM-LC function of the form [4]:

$$\Theta_n(y_n,E)=\Theta_{n-1}+a_n(E)y_n+b_n(E)y_n^2,$$

where a_n and b_n are the approximation coefficients, Θ_{n-1} is the mismatch value on the previous layer.

The spatial distributions of the light fields for the 0-th and 1-st diffraction order at the MIHDS output are determined by the expressions:

$$\mathbf{E}_1^n(\eta)=\mathbf{e}_1^{o,n}E_1^{o,n}(\eta)\exp[-i\int_0^{d_n}\mathbf{k}_1^{o,n}d\mathbf{r}]+\mathbf{e}_1^{e,n}E_1^{e,n}(\eta)\exp[-i\int_0^{d_n}\mathbf{k}_1^{e,n}d\mathbf{r}],$$

$$\mathbf{E}_0^n(\xi)=\mathbf{e}_0^{o,n}E_0^{o,n}(\xi)\exp[-i\int_0^{d_n}\mathbf{k}_0^{o,n}d\mathbf{r}]+\mathbf{e}_0^{e,n}E_0^{e,n}(\xi)\exp[-i\int_0^{d_n}\mathbf{k}_0^{e,n}d\mathbf{r}],$$

where $\mathbf{e}_j^{m,n}$ are the polarization vectors; $\xi_0=\xi$, $\xi_1=\eta$, ξ_0 and ξ_1 are the aperture coordinates.

Transition from amplitude distributions of frequency Fourier components of diffracting beams to their angular spectra:

$$E_j^e(\theta)=\int_{-\infty}^{\infty}E_j^e(l)\exp\left[ik_j^e l\theta\right]dl,$$

where $l=\xi_0,\xi_1$ and the angle θ characterizes the direction of the components $E_j^e(\theta)$ relative to the wave normals.

The process of converting the frequency-angular spectra of interacting light beams by the matrix method for extraordinary waves at the output of MIHDS will be represented as:

$$\mathbf{E}^{e,N}=\mathbf{T}^N\cdot\mathbf{E}^0$$

where $\mathbf{T}^N=\mathbf{T}^{e,N}\cdot\mathbf{A}^{e,N-1}\cdot\mathbf{T}^{e,N-1}\cdot\ldots\cdot\mathbf{A}^{e,1}\cdot\mathbf{T}^{e,1}$ is the matrix transfer function of the entire MIHDS; $\mathbf{E}^{e,N}=\begin{bmatrix}E_0^{e,N}(\omega,\theta)\\E_1^{e,N}(\omega,\theta)\end{bmatrix}$, $\mathbf{T}^{e,n}=\begin{bmatrix}T_{00}^{e,n}(\omega,\theta) & T_{10}^{e,n}(\omega,\theta)\\T_{01}^{e,n}(\omega,\theta) & T_{11}^{e,n}(\omega,\theta)\end{bmatrix}$ is the matrix transfer function, $\mathbf{A}^{e,n}$ is the transition matrix for the intermediate layer from [3], $\mathbf{E}^0=\begin{bmatrix}E_0(\omega,\theta)\\0\end{bmatrix}$.

Components of the matrix $\mathbf{T}^{e,n}$:

$$T_{00}^{e,n}=-\frac{C_0^eC_1^ed_n^2}{4\nu_1\nu_0}\int_{-1}^{+1}exp\left[\delta m'(1-y)+\delta^2n'(1-y)^2\right]\cdot\Phi\left(\frac{d'}{b'}+1,2;b'\delta^2\frac{\nu_1}{\nu_0}(1-y^2)\right)dy\cdot(1+y),$$

$$T_{10,01}^{e,n}=-i\frac{C_{1,0}^ed_n}{2\nu_{0,1}}\int_{-1}^{+1}exp\left[\delta m'(1-y)+\delta^2n'(1-y)^2\right]\cdot\Phi\left(\frac{d'}{b'},1;b'\delta^2\frac{\nu_1}{\nu_0}(1-y^2)\right)dy,$$

$$T_{11}^{e,n}=-\frac{C_0^eC_1^ed_n^2}{4\nu_1\nu_0}\int_{-1}^{+1}exp\left[\delta m(1-y)+\delta^2n(1-y)^2\right]\cdot\Phi\left(\frac{d'}{a}+1,2;a\delta^2\frac{\nu_1}{\nu_0}(1-y^2)\right)dy\cdot(1+y),$$

where all the notations are given in [3].

NUMERICAL CALCULATION

$\lambda=1490$ nm; $d_n=15$ μm; $t_n=160$ μm; $\theta_B=15$ degree; $n_{lc}^o=1.535$ and $n_{lc}^e=1.68$ are the ordinary and extraordinary refractive indices for LC, respectively; $n_p=1.535$ is the refractive index for the polymer; parameters for approximating the spatial amplitude of the first harmonic of the refractive index for PPM-LC layers by a function of the form $n(y,c,s,t)=\cosh\left(c\cdot(s\cdot y-t)\right)^{-1}$ are $\{c,s,t\}=\{0.058,\text{-}1.867,\text{-}0.688\}$.

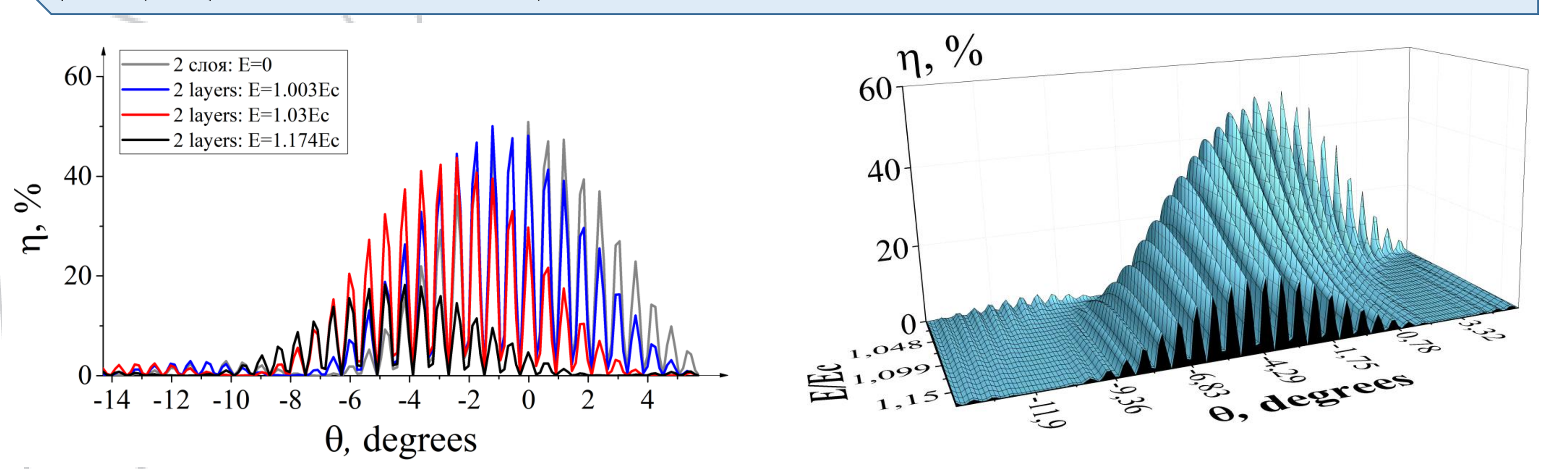

Fig 3. Dependence of diffraction efficiency on reading angle and value of applied electric field

CONCLUSIONS

In summary, this paper presents the results of a study of light diffraction on electrically controlled MIHDS with PPM-LCs having smooth optical inhomogeneity.

The results show that smooth optical inhomogeneity in the depth of diffraction layers with PPM-LCs leads to a significant angular shift of angular selectivity under the influence of an external electric field. This feature can be used for implementation of electrically tunable spectral filters based on PPM-LCs, which can find wide application in optical communication networks, where wave multiplexing technologies are used.

[1] V. O. Dolgirev, S. N. Sharangovich, Bull. Russ. Acad. Sci. Phys. 86 (1), 18 (2022).
[2] S. A. Strelcov, Russ. Phys. J. 58 (5), 663 (2015).
[3] S. V. Ustyuzhanin et al., TUSUR reports (2), 192 (2007).

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