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Electrically controlled optical spectral filters for WDM communication networks based on multilayer inhomogeneous holographic diffraction structures

This paper presents a theoretical model of light diffraction on electrically controlled multilayer inhomogeneous holographic structures formed in photopolymerizing compositions with a high proportion of nematic liquid crystals. The diffraction characteristics of these structures are presented by numerical simulation, demonstrating the possibility of using them as electrically controlled spectral filters for WDM communication networks.

INTRODUCTION

Currently, optical communication systems are rapidly developing and, therefore, scientists are faced with the task of finding not only new, but also efficient and economical elements for such systems from the point of view of production. Diffraction optical elements (DOE) based on multilayer inhomogeneous holographic diffraction structures (MIHDS) formed in thin films (10-100 microns) containing photopolymerizable compositions with nematic liquid crystals (PPM-LC) [1] could find wide application in optical communication networks, for example, as optical spectral filters [2, 3].

The main idea for the implementation of spectral filtering of optical radiation is to use a certain set of thin PPM-LC films with recorded diffraction gratings, which are separated by homogeneous buffer layers. The angular selectivity of the MIHDS is a set of local maxima, while the envelope of the selectivity contour corresponds to a single holographic diffraction structure (HDS). Interpreting local maxima as a bandwidth for certain wavelengths with deviation from the Bragg diffraction conditions, it is possible to use these properties for spectral filtering of optical radiation, and using an external electric field, it is also possible to control the diffraction characteristics of such structures.

Thus, the purpose of this work is to study the diffraction characteristics of electrically controlled MIHDS formed in photopolymerizing compositions with a high content of nematic liquid crystals.

THEORETICAL MODEL OF LIGHT DIFFRACTION ON MIHDS IN PPM-LC

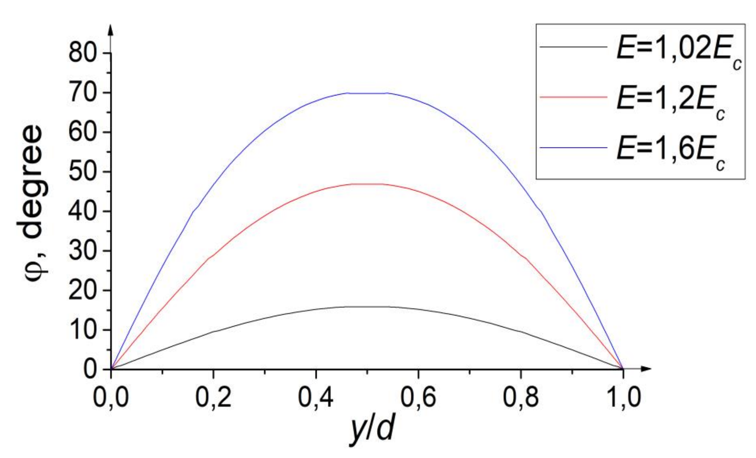

Fig. 1. Dependence of the rotation angle of the LC director on the voltage of the electric field along the thickness of the PPM-LC layer

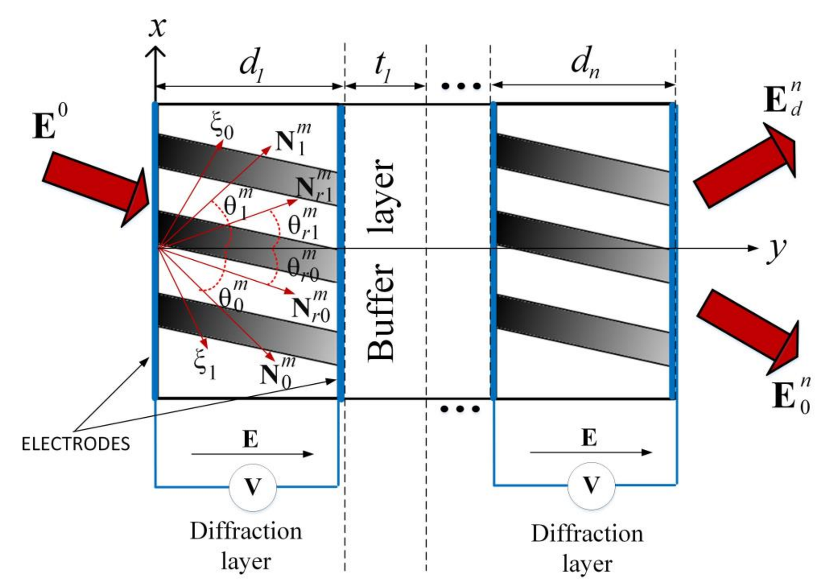

Fig 2. Scheme of light diffraction on MIHDS in PPM-LC

The amplitudes of interacting waves in the case of Bragg diffraction are determined by systems of coupled wave equations in partial derivatives [3]:

$$\mathbf{N}_{r0}^{m,n}\cdot\nabla E_0^{m,n}=-iC_1^{m,n}\cdot n_1^{m,n}\cdot E_1^{m,n}\cdot\exp\left[+i\Theta_n^m\right],$$
$$\mathbf{N}_{r1}^{m,n}\cdot\nabla E_1^{m,n}=-iC_0^{m,n}\cdot n_1^{m,n}\cdot E_0^{m,n}\cdot\exp\left[-i\Theta_n^m\right],$$

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 in [3].

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:

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

where $\mathbf{T}^{m,N}=\mathbf{T}^{m,N}\cdot\mathbf{A}^{m,N-1}\cdot\mathbf{T}^{m,N-1}\cdot\ldots\cdot\mathbf{A}^{m,1}\cdot\mathbf{T}^{m,1}$ is the matrix transfer function of the entire MIHDS; $\mathbf{E}^{m,N}=\begin{bmatrix}E_0^{m,N}(\omega,\theta)\\E_1^{m,N}(\omega,\theta)\end{bmatrix}$, $\mathbf{T}^{m,n}=\begin{bmatrix}T_{00}^{m,n}(\omega,\theta) & T_{10}^{m,n}(\omega,\theta)\\T_{01}^{m,n}(\omega,\theta) & T_{11}^{m,n}(\omega,\theta)\end{bmatrix}$ is the matrix transfer function; $\mathbf{A}^{m,n}$ 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 $\mathbf{T}^{m,n}$:

$$T_{00}^{m,n}=-\frac{C_0^mC_1^md_n^2}{4\nu_1\nu_0}\int_{-1}^{+1}\exp\left[\delta m(1-y)+\delta^2n(1-y)^2\right]\cdot\Phi\left(\frac{d'}{a}+1,2;a\delta^2\frac{\nu_1}{\nu_0}(1-y^2)\right)dy\cdot(1+y)$$
$$T_{10,01}^{m,n}=-i\frac{C_{1,0}^md_n}{2\nu_{0,1}}\int_{-1}^{+1}\exp\left[\delta m'(1-y)+\delta^2n'(1-y)^2\right]\cdot\Phi\left(\frac{d'}{b'},1;b'\delta^2\frac{\nu_1}{\nu_0}(1-y^2)\right)dy$$
$$T_{11}^{m,n}=-\frac{C_0^mC_1^md_n^2}{4\nu_1\nu_0}\int_{-1}^{+1}\exp\left[\delta m(1-y)+\delta^2n(1-y)^2\right]\cdot\Phi\left(\frac{d'}{a}+1,2;a\delta^2\frac{\nu_1}{\nu_0}(1-y^2)\right)dy\cdot(1+y)$$

where all the notations are given in [3].

NUMERICAL CALCULATION

$\lambda_0=633$ nm is the wavelength of the recording; $\theta_B=40^0$ is the recording angle between the beams; $d_n=15$ μm is the thickness of the diffraction layer; $t_n=70.5$ μm is the thickness of the buffer layer; $\lambda_{read}=1331$ nm is the reading wavelength; $n_{lc}^o=1.535$ 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; Bragg angle for the reading wave is $\theta_B=46^0$; $N=2$ is the number of diffraction layers.

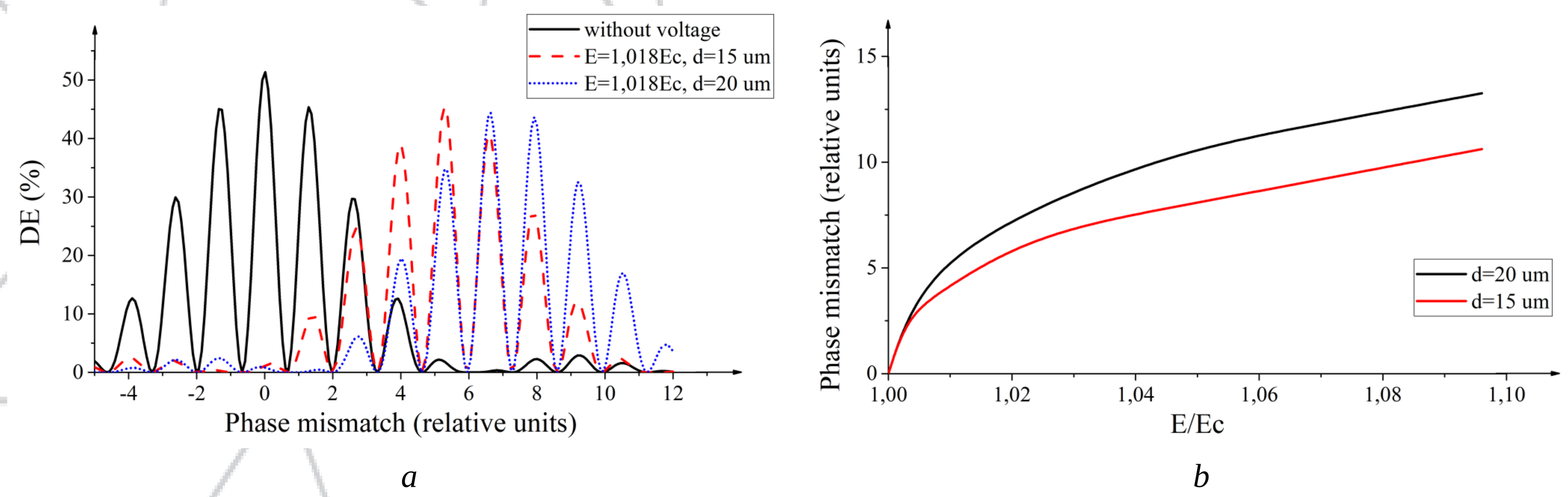

Fig 3. Dependence of (a) the diffraction efficiency and (b) the coefficient of displacement of the angular selectivity of a two-layer HDS when controlling an external electric field when reading on extraordinary waves

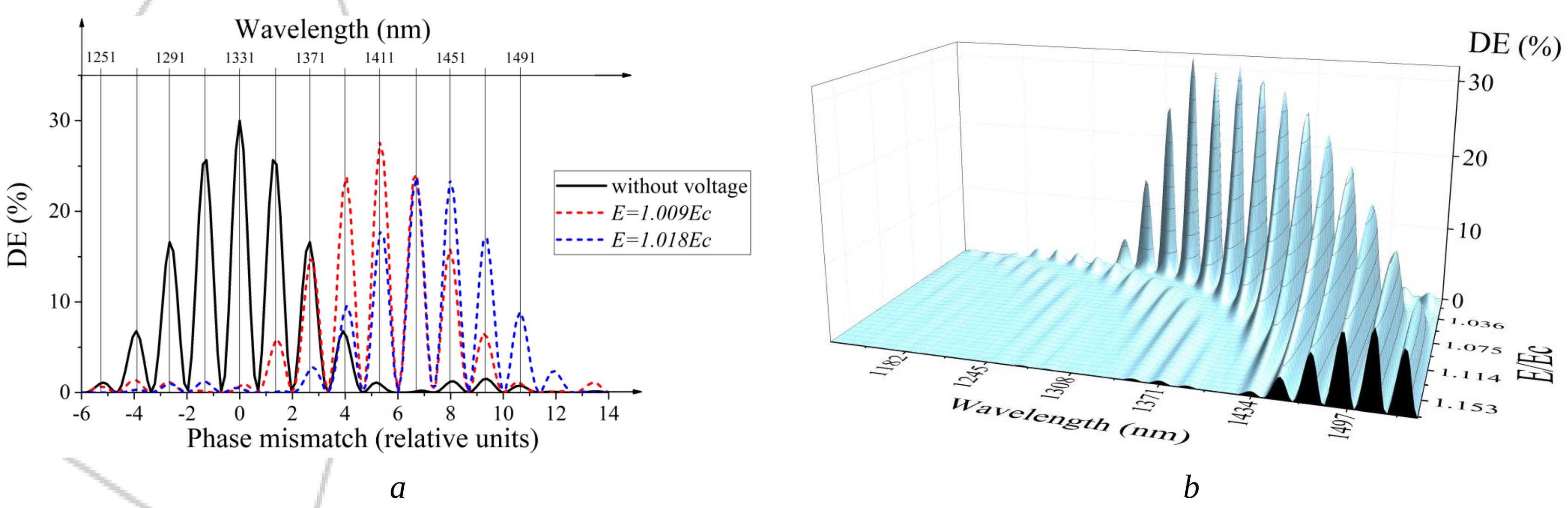

Fig 4. The dependence of the diffraction efficiency on phase mismatch and (a) discrete and (b) smoothly varying electric field when reading on extraordinary waves

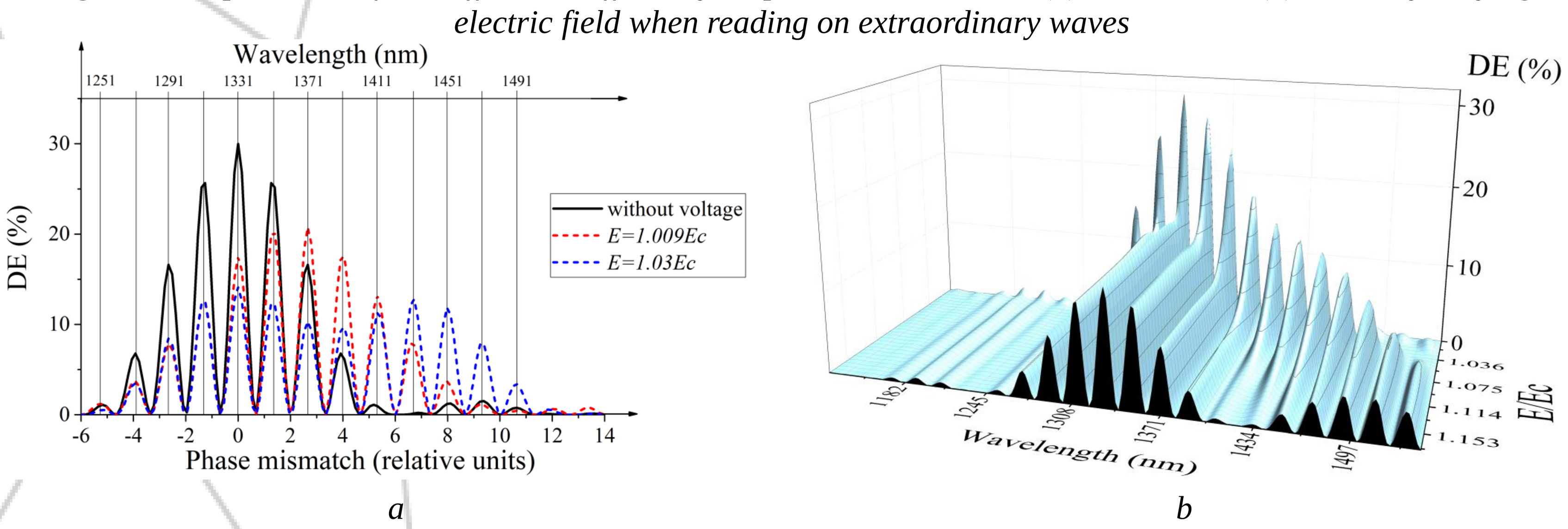

Fig 5. The dependence of the diffraction efficiency on the phase detuning and (a) discrete and (b) smoothly varying electric field when reading on a light wave with a polarization azimuth of 45 degrees

CONCLUSION

Thus, this paper presents a mathematical model that describes the process of light diffraction on electrically controlled multilayer diffraction structures that can be formed by the holographic method in photopolymerizing compositions with a high concentration of nematic liquid crystals.

According to the presented mathematical model, numerical calculating of diffraction characteristics for two-layer structures was carried out. It was found that when an electric field is applied to the diffraction layers, the angular selectivity can be shifted. In this case, the shift is due to the influence of the integral phase shift, which has a dependence on the value of the electric field. This specificity can be applied to implement electrical control of the spectral channel distribution, for example, for channel reconfiguration of CWDM multiplexers.

Sources

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