Studying the process of holographic formation of multilayer inhomogeneous PPM-LC diffraction structures

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Abstract. The article describes a theoretical model for the formation of a multilayer diffractive holographic structure (MIHDS) based on a photopolymer composition including liquid crystals (LC). We presented mathematical modeling of spatial profiles kinetics of the refractive index of the first harmonic of MIHDS considering the photoinduced light absorption (PLA) of the non-optimized and optimized composition. Numerical modeling has shown that optimization of the composition of MIHDS at different thicknesses of the diffraction layer requires a difference in the concentration of the dye–sensitizer for subsequent layers.

1. Introduction
The unique properties of multilayer inhomogeneous holographic diffraction structures, caused by the interaction of optical radiation during their formation and diffraction of light on them, are being investigated by a number of scientists from different countries of the world [1-7]. Due to interference effects occurring between diffraction layers separated by an intermediate buffer layer, a complex type of selective response of optical emission can be observed at the output of this structure. The response is characterized by a number of local maxima, which number and width is defined by the thicknesses of the holograms and buffer layers. In this case the envelope of the selectivity contour coincides with the selectivity contour of single holograms [3, 5]. These properties of such multilayer structures can have the potential of finding application in components of optical devices, for example, in spectral filters, sensors, interconnections, and femtosecond laser optics, along with the prospect of application in communication equipment, which in turn can lead to development of a new element base in fiber optics. optical communication lines of various scales [4, 8].

However, the task of finding a way to dynamically control such structures is currently relevant. In our work, we propose the use of a photopolymer material with liquid crystals (PPM-LC) as a photosensitive environment. As is known, the director of the liquid crystal is sensitive to electrical impact and can alter its spatial orientation, which also leads to a change in the condition of propagation of electromagnetic waves [9-11]. Therefore, using an external electrical effect on the layers with holograms recorded in the PPM-LC, there is an opportunity to dynamically regulate the diffraction characteristics of the MIHDS.

Therefore, the study of the process of holographic formation of multilayer inhomogeneous PPM-LC diffraction structures at this stage is relevant.
2. Theoretical part
The transmission geometry of the recording of diffraction structures in the MIHDS considered in this work is two incident beams of monochromatic waves $E^0(t,r)$ and $E^1(t,r)$ accordingly, at angles and onto the MIHDS composition with PPM-LC (Figure 1).

$$E'(t,r)$$

$$E(t,r)$$

![Figure 1. Geometry of the formation of MIHDS.](image)

Due to the anisotropic properties of the PPM-LC sample, the light beam inside it divides into an ordinary and an extraordinary wave. The distribution of the intensity of the interference pattern of the light field for ordinary and extraordinary waves in PPM-LC with allowance for photoinduced light absorption (PLA) on the $n$-th layer of the MIHDS is regulated by the equation [9]:

$$I^{n,m}(t,r) = \sum_{m=0,e} I^{n,m}(t,r) \cdot \left[ 1 + m^{n,m}(t,r) \cdot \cos(K^{n,m} \cdot r) \right],$$

where $m^{n,m}(t,r) = 2 \sqrt{I^{n,m}_0(t,r) \cdot I^{n,m}_1(t,r)} \cdot (\mathbf{e}_0 \cdot \mathbf{e}_1) / \left( I^{n,m}_0(t,r) + I^{n,m}_1(t,r) \right)$ - is a local contrast of the interference pattern; $I^{n,m}_0(t,r) = I^{0,n,m}(t,r) \cdot \exp[-\alpha^{n,m}(t,r) \cdot y / \cos(\theta_m^0)]$; $I^{n,m}_1(t,r) = I^{1,n,m}(t,r) \cdot \exp[-\alpha^{n,m}(t,r) \cdot y / \cos(\theta_m^0)]$; $I^{j,n,m}(t,r) = I_j^{n,m}(r) \cdot 2^j$; $j = 0,1$; $m = o,e$.

$K^{n,m} = k_0^{n,m} - k_1^{n,m}$ - is a vector of the grating; $r$ - is a radius-vector; $k_j^{n,m}$ - are wave vectors of beams; $n = 1,2,...N$ - is a number of layer; $\alpha^{n,m}(t,r) = \alpha_2^n + \alpha_1^n \exp \left[ - \left( I^{n,m}_0(t,r) / \cos(\theta_0^m) + I^{n,m}_1(t,r) / \cos(\theta_1^m) \right) \cdot y / T_a \right]$ - is PLA index; $\alpha_2^n = \alpha_0^n k_0^n$ - are substrate absorption index and dye–sensitizer absorption index; $\alpha_0^n$ - is an absorption of one dye–sensitizer molecule; $\varphi$ - is a quantum yield of the dye–sensitizer; $T_a = 1 / (\varphi \alpha_0^n \max[I^{n,m}_0(t,r) / \cos(\theta_1^m)]).

The interference patterns formed when falling on the boundary of the MIHDS with PPM-LC are constructed on extraordinary and ordinary waves due to the anisotropy of the PPM-LC. During diffusion, the monomer diffuses from dark places into the bleached part, forming a polymer chain and thereby displacing LC molecules into the dark part, forming a diffraction grating.

The solution for the spatiotemporal distribution of the first harmonic of the refractive index is sought in the general case from the equations of the kinetics of the photopolymerization-diffusion formation of diffraction structures in the PPM-LC and is composed of two terms characterizing the amplitude profiles of the polymer and LC [7]:

$$n_1^{n,m}(t,y) = n_1^{n,m}(t,y) + n_{1LC}^{n,m}(t,y)$$ (1)
where \( n_{1p}^{n,m}(t, y) = \delta n_p^{n,m} \cdot \frac{2^k}{b_{1p}^{n,m}(t, y)} \int_{0}^{1} n_{0n}^{n,m}(\tau, y) \left[ p_{n,m}^{n,m}(\tau, y) \cdot k \cdot m_{n,m}^{n,m}(\tau, y) - f_{n,m}^{n,m}(\tau, y)\right] (1 + 1.5L_{n,m}^{n,m}(\tau, y)) d\tau \) and \( n_{1LC}^{n,m}(t, y) = \delta n_{LC}^{n,m} \cdot \frac{D_{LC}^{n,m}}{D_m} \int_{0}^{1} f_{n,m}^{n,m}(\tau, y) \cdot m_{n,m}^{n,m}(\tau, y) d\tau \) - are amplitude profiles of polymer and LC gratings; \( \delta n_p^{n,m} \) and \( \delta n_{LC}^{n,m} \) - are coefficients of transformation in the refractive index of an LC and polymer; \( D_{LC} \) and \( D_m \) - are diffusion coefficients of LC and monomer; \( b_{n,m}^{n,m}(t, y) = T_{p,m}^{n,m}(t, y)/T_m \) - is the ratio of polymerization time to diffusion time; \( T_m = 1/(K_1^2 \cdot D_m) \) - monomer diffusion time; \( T_{p,m}^{n,m}(t, y) = (2K_b/(\alpha \cdot \beta \cdot \tau_0) \cdot [K_n^m]^{n,m}(t, y))^{k} / K_g \) - polymerization time; \( K_g \) - polymer chain growth parameter; \( K_b \) - polymer chain breaker parameter; \( \beta \) - photoinitiation parameter; \( \tau_0 \) - relaxation time of an excited dye–sensitizer molecule; \( K_n^m \) - dye–sensitizer concentration; \( L_{n,m}^{n,m}(t, y) = k(k-1)\frac{m_{n,m}^{n,m}(t, y)^2}{4} \); \( n_{0n}^{n,m}(t, y) = \exp[-s \cdot (1 - p_{n,m}^{n,m}(t, y))] \); \( k \) - is nonlinearity parameter of photopolymerization process; \( s \) - diffusion rate parameter; \( I_{0n}^{n,m}(t, y) \) - intensity in the \( n \)-th layer; \( f_{n,m}^{n,m}(t, y) = \frac{2^k}{b_{n,m}^{n,m}(t, y)} \cdot \left[ p_{n,m}^{n,m}(\tau, y) \cdot m_{n,m}^{n,m}(\tau, y) \cdot I_{0n}^{n,m}(\tau, y) \cdot \exp\left(-t I_{0n}^{n,m}(T, y) / b_{n,m}^{n,m}(T, y)\right) \right] \cdot I_{0n}^{n,m}(T, y) \cdot (1 + 1.5L_{n,m}^{n,m}(T, y)) dT d\tau \).

3. Numerical simulation

Using equation (1), when recording with beams with polarization corresponding with ordinary natural waves and the same content for every layer, the amplitude spatial profiles of the 1st harmonic of the refractive index were numerically calculated taking into account the PLA for a four-layer holographic diffractive structure (Figure 2). For the numerical calculation, the following parameters were used: \( d = d_1 \ldots d_4 = 45 \) and \( 85 \) \( \mu m \), \( t_p = 135 \) \( \mu m \), \( \alpha_2 = 0.016 \ Np \), \( \alpha_1 = 2.2 \ Np \), \( 20=10 \) degrees, \( \lambda = 633 \) \( nm \), \( \delta n_p = 0.008 \), \( \delta n_{LC} = 0.2 \delta n_p \), \( k = 0.5 \), \( D_m = 0.72 \), \( s = 1 \), \( D_m = D_{LC} \).

![Figure 2](image)

**Figure 2.** Kinetics of the spatial profiles of the first harmonic of the refractive index of MIHDS with the same concentration of each layer, with allowance for PLA for different equal layer thicknesses at: (a) \( d = 45 \) \( \mu m \) and (b) \( d = 85 \) \( \mu m \), subsequently.
With the same content of every layer, the amplitude profiles for the first harmonic of the refractive index are different. It happens because of the enlightenment of the material due to the photoinduced absorption of the material (PLA) which alters the recording conditions for each of the gratings at each time instant. The composition with increased thickness has a large amplitude of the first harmonic due to the lesser influence of the dye–sensitizer on the absorbing quality of the material.

Through transforming the internal parameters of PPM-LC, in particular, increasing the concentration of the dye–sensitizer for subsequent layers, it is possible to achieve structures in which the amplitude profiles of the refractive index are uniform and similar to each other. This is due to the need to accelerate the photopolymerization processes for subsequent layers, where the light intensity is lower than on the previous layers.

Optimized by transforming the internal parameters of the next three layers, the kinetics of the formation of amplitude spatial profiles of the refractive index for the first harmonic, taking into account the PLA at different material thicknesses, are presented in Figure 3.

![Figure 3](image.png)

**Figure 3.** Optimized kinetics of spatial profiles of the refractive index of the first harmonic of MIHDS with different concentrations of layers, taking into account the PLA for different equal layer thicknesses at: (a) \(d = 45 \, \mu\text{m}\) and (b) \(d = 85 \, \mu\text{m}\), subsequently.

Figure 3 shows that the selection of the value of the concentration of the dye–sensitizer for the next three layers makes it possible to achieve spatial profiles of the refractive index that are practically equal in amplitude for each layer. At the same concentration of the sensitizing dye for the first layer, but at different thicknesses of the diffraction layers, the process of formation of the amplitude profiles is not the same. To obtain an optimized composition for a four-layer holographic diffraction structure at different diffraction layer thicknesses, different dye concentrations are also required for subsequent layers.

4. Conclusion

Therefore, because of selecting the parameters of the material for every layer, there is possibility to obtain a MIHDS with the required diffraction characteristics. And the approximation of the amplitude profiles to homogeneous ones can help to reduce the distortion of the selective response type when solving the diffraction problem. When choosing an optimized composition, it is necessary to take into account the thickness of the diffraction layer.

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