Optimal period for diffraction gratings recorded in polymer dispersed liquid crystals

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New diffusion model of recording diffraction gratings in the media of PDLC is described in which besides diffusion of monomer molecules also diffusion of polymer molecules and non-locality of diffusion coefficient are taken into account. It lets us to explain why diffraction efficiency is low for low and high values of intensities of grating recording beam. With the considered model, we have theoretically got optimal period for grating recording.

Keywords: liquid crystal, polymer, grating, diffraction.

1. Introduction

In the recent years, photo polymeric materials have attracted researchers attention. They have sequence of advantages against other types of recording materials such as photo resistors, gelatins, and so on. Polymer dispersed liquid crystal (PDLC) medium is convenient for information recording and storage [1–4]. The main advantage of such media is that we can follow up the appearing of formations in the real time [5]. In this composite material, polymer serves as a matrix where the molecules of liquid crystals are dispersed as drop domains. Optical properties of the obtained PDLC materials basically depend on the spatial distribution and morphology of drop-shaped domains, arrangement of LC director in the drops, dimensions of the liquid crystalline formations, and so on. The arising of the forms is caused by modulation of a concentration of the drops and polymer matrix holes. PDLC media have mechanical properties of polymer matrix and optical anisotropy of LC dispersed in the matrix [6]. That anisotropy, in the case of weak anchoring energy at domains’ walls, could be controlled by external fields. Mechanical strength and easy controllable anisotropy of such media provide possibility of creation of plane LC monitor, microlenses with controllable focal distances [7], and so on. The simplest forms with the discussed properties are the diffraction gratings with periodical distribution of concentration and refractive index, which are produced with the help of interference pattern of two plain waves [8,9]. In Refs. 10, 11, and 12, the recording dynamics in photopolymers dispersed liquid crystals media of gratings and choosing of optimal parameters for receiving effective gratings are considered. The forms appear with the following scheme, photomonomer transforms into a polymer because of chain reaction which arises from light affection. At that, if the photomonomer is being illuminated with the interference pattern, then in the regions of space where the intensity of light is higher, the process passes faster [13]. When monomer-polymer transformation takes place, spatial redistribution of monomer concentration arises. Molecules of the monomer diffuse from the dark regions to the illuminated regions because the decrease in monomer molecules takes place in those regions. Correspondingly, in the illuminated regions, the amount of polymerised monomers increases and LC is being pushed out from those places. So, modulation of refractive index arises and, consequently, diffraction grating arises, too. Monomer and LC in PDLC media is being chosen in such a way that they dissolve in each other. Situation is different in the case of polymer and liquid crystal. There is a phase division between them, and if there is a polymer in some volume, liquid crystal is being forced out from that volume.

In fact, in the dark regions concentration of a liquid crystal is higher, than in light regions, what leads to anisotropic diffraction grating formation, which has controllable modulation of refractive index. There are sequences of models describing these processes [13,14]. Nevertheless, in the case of low intensities of grating recording laser, the process models give incorrect results because in that case modulation depth of the recorded diffraction grating is maximal [9]. As we will discuss below, this does not coincide with reality. As it can be seen from qualitative experiments, for very high and very low intensities, modulation of polymer concentration and efficiency of recorded diffraction gratings are small.

A new model is described, where besides diffusion of monomer molecules, diffusion of polymer molecules and non-locality of diffusion coefficient are taken into account. This gives an opportunity to explain entirely the recording dynamics of diffraction gratings in PDLC media. In the
frame of the considered model, it is theoretically shown that there is a spatial period at which diffraction efficiency is maximal.

2. Diffusion model with consideration of polymer diffusion

Photopolymeric systems basically consist of monomer, polymeric cross linking agent, and photoinitiator. Monomer is being polymerized under light influence, and percentage of polymerized molecules increases proportionally to the illuminating time. Concurrent with the process of monomer-polymer transformation, diffusive processes are being slowed down and, finally, broken off, what means that coefficient of monomer diffusion decreases during exposition. It can be explained in the following manner, increasing polymer concentration makes substance more opaque for monomer molecules. Dynamics of diffraction gratings recording in PDLC media is being widely investigated and is described with, so-called, diffusion equations of polymerization. There are two basic models for polymerization, local [5,8] and non local one [9,13,14]. In the first one, it is considered, that coefficient of polymerization in each point depends on illumination value at that point, and in the second one it is considered that coefficient of polymerization also depends on the illumination value at the neighbouring points. In the following discussion, we will concentrate only on the case of non-local response, as its generality. Let us consider dynamics of diffraction gratings recording in PDLC media which arises from the result of two plane waves’ interference. Spatial distribution of two plane waves can be presented in the following form [4]

\[ I(x,t) = I_0(1 + V \cos(kx)), \]  

(1)

here \( I_0 \) is the average intensity, \( V \) is the visibility of an interference pattern, \( k = 2\pi/\Lambda \), and \( \Lambda \) is the period of interference pattern. Schematic representation of diffraction grating recording is shown in Fig. 1.

But in the case of low intensities of the recording laser, the results obtained with this model differ from experimental results. In this case, diffraction efficiency of a grating achieves its maximal value. Such a result is incorrect. Experiments show that in the cases of very high and very low intensities, diffraction efficiencies of the recorded gratings are low [15]. To develop a model which will explain experimental results in the proper way, let us take into account the following fact. In the lightened regions, monomer is being polymerized and, naturally, in that region concentration of monomer decreases. Diffusive processes of the monomer tend to fill up the lack of concentration in the lightened regions, i.e., monomer diffusion from dark regions to the lightened ones takes place. On the other hand, concurrent with polymerization, the velocity of diffusive processes in the medium decreases. Consequently, if the characterization times of the polymerization be incomparably smaller than monomer diffusive process’ ones, then it would not be modulation of concentration. Otherwise, if monomer has time to diffuse from dark regions to light regions completely, and concurrent with polymerization the decrease in diffusion would not impede monomer diffusion, then maximal modulation of concentration will be obtained. For low intensities, only this case occurs because of a very slow process of polymerization, the diffusive processes cannot be stopped and maximal modulation is obtained.

According to the presented discussions, in the case of low intensities, neglecting of polymer diffusion is rough approximation. Naturally, the processes of polymer diffusion are much slower than monomer’s ones, but, when the times of polymerization are very long even slower diffusive processes would have time definitely average polymer concentration. That is, in the case of slow polymerization, polymer diffusion from the dark to the lightened regions must not be neglected.

So, diffusive equations of polymerization where both polymer and monomer diffusion processes are taken into account will be written in the following form

\[ \frac{\partial U(x,t)}{\partial t} = \frac{\partial}{\partial x} \left( D_U(x,t) \frac{\partial U(x,t)}{\partial x} \right) - \frac{\partial N(x,t)}{\partial t}, \]  

(2)

\[ \frac{\partial N(x,t)}{\partial t} = \frac{\partial}{\partial x} \left( D_N(x,t) \frac{\partial N(x,t)}{\partial x} \right) + \int_{-\infty}^{+\infty} R(x,x') F(x') U(x',t) dx', \]  

(3)

here \( U(x,t) \) is the monomer concentration, \( F(x,t) \) is the local coefficient of polymerization [7,10], and \( D_N \) is the polymer diffusion coefficient. The function \( R(x,x') \) describes spatial non-locality. Unlike previous models, first item in the right-hand side of Eq. (3) describes diffusion of polymer molecules. A member considering spatial non-locality is represented in the form of Gaussian function [13]

\[ R(x-x') = \exp \left( -\frac{(x-x')^2}{2\sigma^2} \right), \]  

(4)