Holographic volume absorption gratings in glass-like polymer recording materials

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Introduction

The development of volume phase gratings written by two-wave-mixing in glass-like polymer storage materials based on poly (methylmethacrylate) (PMMA) and its thermostable derivative (copolymer with acrylic acid) with distributed phenanthrenequinone (PQ) is investigated experimentally and theoretically. The maximal diffraction efficiency is considered in dependence on the grating period. The redistribution processes of the molecules are described with a one-dimensional diffusion model yielding the existence of a non-local response in the photopolymer layer, and the corresponding non-local response length of PQ is found experimentally.

Experimental results

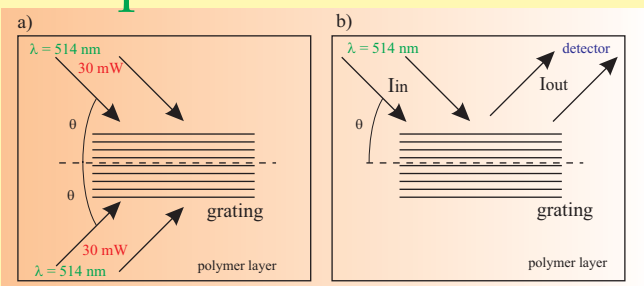

Fig. 1. Scheme for recording (a) and reconstruction (b) of the grating in the polymer film layer

The diffraction efficiency (DE) was measured as the ratio of diffracted beam intensity to intensity of the input beam

$$DE = \frac{I_{out}}{I_{in}} \cdot 100\%$$

The period of the gratings $d = \frac{\lambda}{2\sin\theta}$

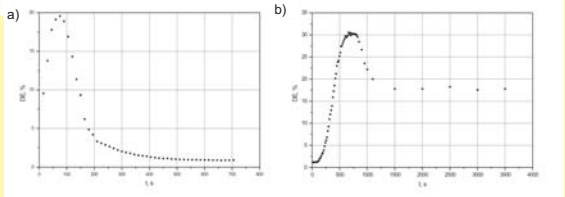

Fig. 2. Typical diffraction efficiency of PMMA+PQ (a) and the copolymer of MMA+AA+PQ (b) versus recording time.The angle 2θ is 32° within the medium

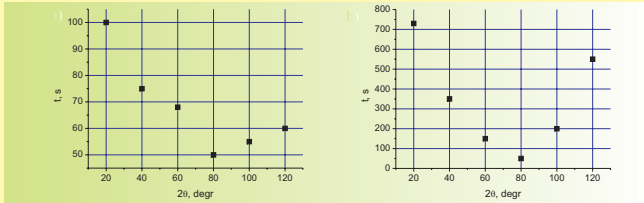

Fig.3. Dependence of the time for achieving the maximum diffraction efficiency on the angle between beams for a) PMMA+PQ and b) PMMA+AA+PQ polymer gratings

Theoretical approach

Change of the PQ concentration [1]:

$$\frac{\partial C(x,t)}{\partial t} = \frac{\partial}{\partial x}[D(x,t)\frac{\partial^2}{\partial x^2}C(x,t)] - \int_{-\infty}^{+\infty} R(x,x')\cdot F(x',t)C(x',t)dx']$$

Nonlocal response of the medium:

$$R(x-x') = \frac{\exp[-(x-x')^2/2\sigma]}{\sqrt{2\pi\sigma}}$$

Modulation of the photoproduct:

$$\frac{\partial N(x,t)}{\partial t} = \varepsilon \cdot I \cdot N(x,t)$$

Concentration expressions for the first two harmonics:

$$\begin{cases} \frac{\partial C_0(t)}{\partial t} = -F_0 \cdot C(t) - \frac{F_0 V}{2} C_1(t) \\ \frac{\partial C_1(t)}{\partial t} = -F_0 \cdot V \cdot e^{\frac{-K^2\sigma}{2}} \cdot C_0(t) - F_0 \cdot [e^{\frac{-K^2\sigma}{2}} + R]\cdot C_1(t) \end{cases}$$

Modulation of the photoproduct:

$$N(x,t) = N_0(t) + N_1(t)\cdot\cos(Kx) + N_2(t)\cdot\cos(2Kx) + \ldots$$

For first two harmonics we receive:

$$N_0(x,t) = \int_0^t [F_0 \cdot C_0 \cdot (t) + \frac{FV}{2} C_1(t)]d(t)$$

$$N_1(x,t) = \int_0^t [F \cdot V \cdot e^{\frac{-K^2\sigma}{2}} C_0(t) + F(e^{\frac{-K^2\sigma}{2}} + R)C_1(t)]dt$$

$C(x,t)$ - modulation of the PQ - concentration;
D - diffusion coefficient;
$F(x',t')$ - copolymerization rate;
$R(x,x',t,t')$- nonlocal response;
$\sqrt{\sigma}$- nonlocal response length;
$N(x,t)$- modulation of polymer
ε- extinction coefficient;
I - light intensity;
V- fringe visibility;
K - spatial frequency of the grating;
$K=\frac{2\pi}{d}$, d - grating period;
n - refractive index of the layer;
Ri – refraction and Δci - change of concentration of the i-th component

$$\Delta n = \frac{(n^2+2)^2}{6n}\sum_i R_i \Delta c_i$$

- Lorentz Lorenz's formula

Diffraction efficiency [2]:

$$DE = \tanh^2\left(\frac{\pi \Delta n T}{\lambda \cos\theta}\right)$$

The general form of the theoretical curves in Fig. 5 coincides with the experimental ones (Fig. 3). The agreement of the experimental and theoretical results allows us to suppose that the existence of the extreme of the time for reaching the maximal DE versus the angle between the beams is due to a non-local response of the PMMA+PQ and PMMA+AA+PQ polymer layers. The fitted average non-local response length of the PQ lies in the range between 30 nm and 70 nm.

Parameters for theoretical calculations:
refractive index is 1.5;
emulsion thickness is 10 μm ;
wavelength is 514 nm;
input intensity of each beams is 210 mW/cm^2;
diffusion coefficient is 11*10^{-17} cm^2/s;
constant of copolymerisation is 5.676*10^{-5} W$^{-0.5}$s^{-1}cm.

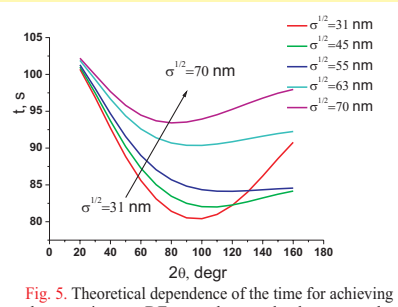

Fig. 5. Theoretical dependence of the time for achieving the maximum DE on the angle between the interfering beams for different values of the non-local response length

Agreement of the experimental and theoretical results

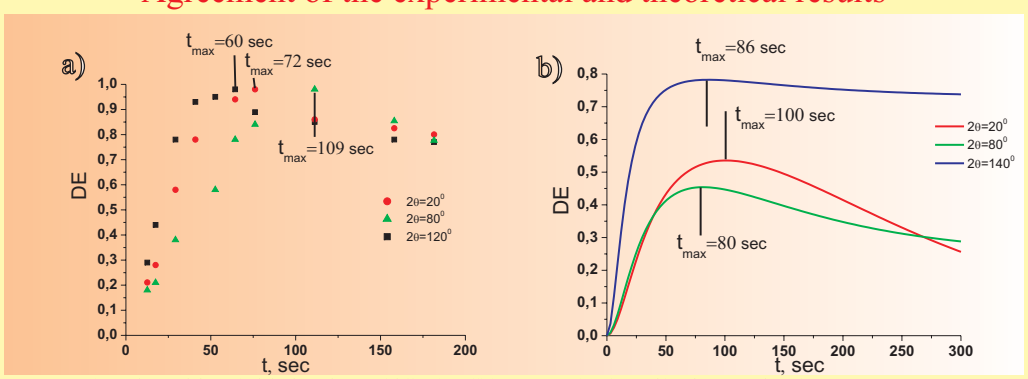

Fig.4. Experimental (a) and theoretical (b) dependences of diffraction efficiency versus time for reaching the maximal DE for input angles 20°, 60°, and 140°. D =11*10^{-17}cm^2/s and the non-local response length is 31 nm

Fig. 4 shows the experimental and theoretical DE curves versus time for input angles, changing from 20° to 140°, and the fit value of the non-local response length of 31 nm. The theoretical results also show that the increase of the interaction angle leads to the decrease of the time for reaching the maximal DE up to a certain angle. Above this angle the corresponding times again increase. In our case this time decreases from 100 s (angle 20°) up to 80 s (80°) and then increases up to 86 s (140°).

1. J.T. Sheridan and J.R. Lawrence,"Nonlocal-response diffusion model of holographic recording in photopolymer", J. Opt. Soc. Am. A 17, No.6, 1108-1114 (2000).
2. H. Kogelnik, „Coupled wave theory for thick hologram gratings", Bell Syst. Tech. J. 48, 2909 (1969).