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Evanescent (surface) wave holographic recording in thin polymeric film

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Abstract. Holographic grating recording with surface evanescent waves is reported. Owing to the small penetration depth the interference pattern is sorted in a 200 nm thick polystyrene film, sensitized with ON-stilbene. The absorption distribution in the recording medium is analysed in the small attenuation index approximation. The diffraction efficiency dependence on time and temperature is also investigated.

1. Introduction

The evanescent part of the electromagnetic wave, resulting from the total internal reflection, has been used for studying thin films for more than 30 years [1]. At the end of the 1960s, almost simultaneously Nassenstein [2] and Bryngdahl [3] made use of the interference between surface waves for holographic recording, using the evanescent wave propagation along the interface between two materials with different refractive indices. A typical feature of this type of hologram is that the interference pattern is stored in a thin layer of the recording medium with a thickness of the order of the evanescent wave's penetration depth. Depending on the recording conditions, it varies from fraction of a micron to microns in the visible region of the spectrum, enabling holographic recording in very thin films.

The present work reports results from the investigations of surface evanescent wave recording in a 200 nm film of polystyrene, sensitized with ON-stilbene, whose thickness is comparable to the penetration depth of the evanescent wave.

2. Theory of the surface evanescent-wave holographic recording

Important for all holographic arrangements is the so-called interference term, describing the interaction two waves with intensities: I_1 and I_2 with phase difference $\Delta\Phi$:

$$I_{12} = 2(I_1 I_2)^{1/2} \cos \Delta\Phi. \quad (1)$$

In the case of holographic recording using a plane wave with an intensity I_p, falling normally onto the interference of two media with refractive indices n_1 and n_2 and an evanescent wave I_e the interference is given by

$$I_{12} = 2(I_p I_e)^{1/2} \cos 2\pi/\lambda(x \sin\varphi_1 - z n_2) \quad (2)$$

where $I_p = I_{p0}\exp(\mathrm{i}k_2 z)$ and $I_e = I_{e0}\exp(-z/z_0)\exp(\mathrm{i}k_1 x\sin\varphi_1)$ with wave vectors $|k_i| = 2\pi n_i/\lambda_0$ and $z_0 = \lambda_0/2\pi n_1(\sin^2\varphi_1 - n^2)^{1/2}$.

The condition for total internal reflection (TIR) is $\sin\varphi_1 > n_2/n_1 = n$, and λ_0 is the vacuum wavelength.

For the maximum modulation we need $I_{p0} = I_{e0} = I_0$ at the interface $z = 0$.

Following [4], we can calculate the corresponding intensities in the second recording medium with complex refractive index $n_2^* = n_2(1 + \mathrm{i}\kappa_2)$:

$$I_{p,e} = I_0 \frac{4n_1^2\cos^2\varphi_1}{(n_1\cos\varphi_1 + u)^2 + v^2}\exp(-4\pi v z/\lambda_0) \tag{3}$$

where $u^2 - v^2 = n_2^2(1-\kappa^2) - n_1^2\sin^2\varphi_1$ and $uv = n_2^2\kappa_2$ [5].

We shall consider the case of small attenuation index $\kappa_2 \ll 1$ that corresponds to the weak absorption coefficient $\alpha = 4\pi n_2\kappa_2/\lambda_0$. In this case $u \approx n_2$ and $v \approx n_2\kappa_2$ and

$$I_e = I_0\exp(-2z/z_0)\frac{4\cos^2\varphi_1}{1-n^2}\left[1 - \frac{\alpha n\cos\varphi_1 z_0}{n_1(1-n^2)}\right]. \tag{4}$$

It can be shown easily that the first two terms in equation (4) describe the intensity of the evanescent wave in the case of a non-absorbing second medium—$\alpha = 0$. Introducing the effective thickness according to [4]: $d_e = \lambda_0/2\pi n_2\kappa_2 = 2/\alpha$, the relation (4) can be written as

$$I_e = I_{e(\alpha=0)}(1 - \alpha d_e). \tag{5}$$

The effective thickness is

$$d_e = \frac{n\lambda_0\cos\varphi_1}{\pi n_1(1-n^2)(\sin^2\varphi_1 - n^2)^{1/2}}. \tag{6}$$

As expected, equation (6) coincides with the definition given by Harrick [1] for the attenuated total internal reflection spectroscopy for s polarization in the bulk for weak absorption $\alpha d_e < 0.1$.

For the plane wave from (3) we have

$$I_p = I_0\frac{4n_1^2}{(n_1+n_2)^2}\exp(-4\pi n_2\kappa_2 z/\lambda_0) = I_0\exp(-\alpha z) \tag{7}$$

which is the mathematical representation of the Lambert–Beer law.

Substituting the obtained expressions for the intensities of the evanescent and plane waves, we obtain for the interference term

$$I_{12} = I_0\frac{8\cos\varphi_1}{(1+n)(1-n^2)^{1/2}}\left(1 - \frac{\alpha d_e}{2}\right)\exp\left(\frac{-z}{z_0}\right)\cos\left[K\left(x - \frac{nz}{\sin\varphi_1}\right)\right] \tag{8}$$

where the wavevector $|K| = 2\pi n_1\sin\varphi_1/\lambda_0$.

3. Experiment and results

Evanescent surface-wave holograms are recorded on the spin-coated 200 nm thick films, containing 1% ON-stilbene. The substrate is made of LaSFN9 heavy flint glass, with refractive index 1.883 at 442 nm wavelength. The holographic set-up is illustrated schematically in figure 1. Recording has been carried out with an He–Cd laser 'Likonix 4270 NB' at a wavelength $\lambda_0 = 442$ nm and intensity of 9 mW cm^{-2} for each interfering beam. The interesting point in the selected configuration is the monitoring beam at 633 nm (He–Ne laser) which is introduced by a second beam splitter (BS2) at an angle of incidence equal to the angle φ of the referent wave.

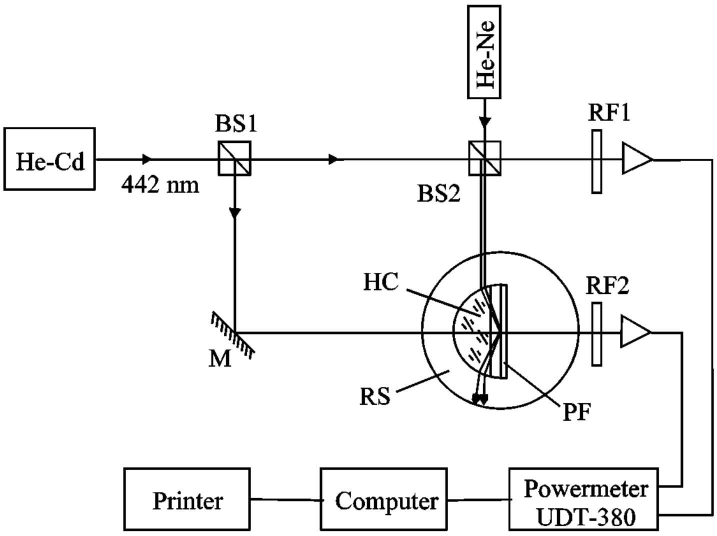

Figure 1. Experimental set-up: BS—beam splitter; RF—red filter; M—mirror; RS—rotary stage; HC—hemicylinder; PF—polymer film.

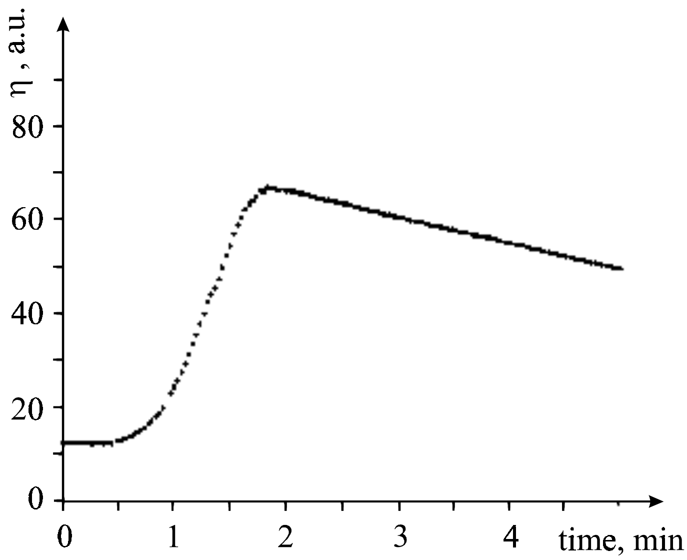

Figure 2. Time dependence of the diffraction efficiency.

The longer wavelength of the monitoring beam and the difference in the refractive indices due to dispersion provide a greater penetration depth compared to that of the holographic recording.

For the total internal reflection prism we use a hemicylinder with a radius 19 mm, made of LaSFN9 heavy flint glass. The optical contact between the hemicylinder and the substrate has been accomplished through the use of methylenoidide (CH_2I_2).

The exposure time is determined by a mechanical shutter. The diffraction efficiency η is estimated by the ratio between the diffracted intensity and the initial intensity of the monitoring red beam, measured with a sensitive UDT-380 power meter. The results from the measurements have been processed in real time with a personal computer. The optical set-up is mounted on a vibration-proof ‘Oriel’ mount providing stability of the interference pattern with a spacing of 251 nm on the surface of the recording medium. The penetration depth z_0 is 97 nm.

The results from the change of the diffraction efficiency with time are illustrated in figure 2. The exposure has been stopped when the diffraction efficiency has reached a maximum. The exposure time is 90 s, and the corresponding energy 1.6 J cm^{-2}.

The influence of the temperature on the recorded gratings is also investigated. With an electric heater (not shown in figure 1), the temperature is changed up to 100 °C. Very fast grating degradation by diffusion has been observed, as illustrated in figure 3.

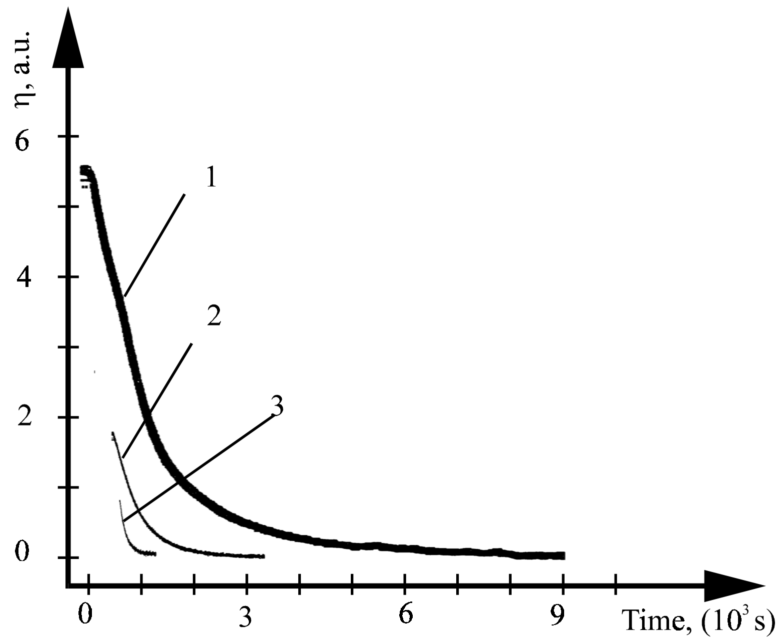

Figure 3. Temperature dependence of the diffraction efficiency. 1. $T = 23$ °C. 2. $T = 60$ °C. 3. $T = 80$ °C.

4. Conclusion

In this paper we have presented the first results from the application of total internal reflection for holographic recording in 200 nm photopolymer film. In our opinion, grating recording by the evanescent surface waves is possible in less than 50 nm thin films with a spacing less than 100 nm. In the present experiment we have used only half of the recording medium.

Investigations in this direction are under way and the results are to be reported shortly.

Acknowledgments

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References

[1] Harrick N J 1967 *Internal Reflection Spectroscopy* (New York: Wiley)
[2] Nassenstein H 1968 *Phys. Lett.* A **28** 49
[3] Bryngdahl O 1969 *J. Opt. Soc. Am.* **59** 1645
[4] Toriumi M, Yanagimachi M and Masuhara H 1992 *Appl. Opt.* **31** 6376
[5] Born M and Wolf E 1970 *Principles of Optics* 4th edn (Oxford: Pergamon) pp 627–30