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Holography with evanescent reference wave*

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Holograms obtained by interference of a typical object wave and an evanescent reference wave are described. Thin films of AZ-1350 photoresist covering an SF 11 glass prism were used as recording layers. Total internal reflection producing an evanescent wave took place at the photoresist layer and the glass prism interface. In the reconstruction process evanescent waves of two lengths were involved. Dependence of the holographic image on reconstruction conditions was examined.

1. Introduction

A considerable interest in evanescent wave fields and their involvement in optical processes has been recently observed. A few theoretical and experimental papers were devoted to holography with evanescent waves [1–4, 6, 7]. All the authors considered holograms occupying very thin area in comparison to the thickness of the recording film. This work gives the account of an experiment in which thin films of absorbing phase material (e.g., photoresist AZ-1350) were used. The holograms obtained occupied the whole volume of the recording medium. The experiment was carried out in order to investigate the properties of photoresist as a material for recording evanescent wave holograms in further work. Method of determining the angle of incidence of reference wave is described and some features of reconstructed images are examined.

2. Evanescent waves and their properties

Evanescent waves are solutions of an inhomogeneous Helmholtz equation

$$(\nabla^2 + k^2)\, U = S \tag{1}$$

where U is a scalar function describing the total field distribution, k is a wavenumber, and S – a distribution function of the light source. These waves vanish on a wavelength's distance from the point of their origin, and their planes of constant phase are not parallel to these of constant amplitude. In areas where light sources do not exist, evanescent waves are generated in optically thinner medium by a totally reflected beam incident from a denser medium, as well as in some other optical processes [5].

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Let us consider a plane, s-polarized wave of wavelength $\lambda = \lambda_0/n_1$ (λ_0 is its wavelength in vacuum) striking a boundary of two media their refraction indices being n_1, n_2 ($n_1 > n_2$). The wave emerging from optically denser medium (Fig. 1) is incident at an angle α greater than the critical angle α_c of total internal reflection determined by equation

$$\sin\alpha_c = n_2/n_1. \tag{2}$$

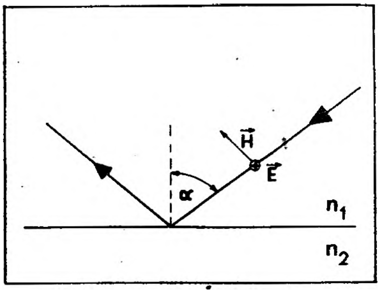


Fig. 1. Total internal reflection of a light beam in a medium optically denser (n_1) at its boundary with optically thinner medium (n_2). The angle of incidence α is greater than critical angle α_c

In thinner medium (Fig. 1) an evanescent wave of wavelength λ_e and penetration depth d [5]

$$\lambda_e = \frac{\lambda_0}{n_1\sin\alpha}, \tag{3}$$

$$d = \frac{\lambda_0}{2\pi n_1}\sqrt{\frac{1}{\sin^2\alpha - \sin^2\alpha_c}} \tag{4}$$

is generated. Its distribution is described by

$$E_e = E_0\exp(-z/d)\exp(iky\sin\alpha). \tag{5}$$

This wave travels along the boundary. Planes of constant amplitude are perpendicular to these of constant phase. The value of Poynting vector is the same as in the incident wave but it is attributed to the boundary plane. Very small fraction of energy penetrates to the thinner medium. At the distance d the energy density is e^{-1} of its value at the reflecting interface.

If an evenescent wave generated in total internal reflection is superimposed with a plane homogeneous wave

$$E_p = E_1\exp(-ikz) \tag{6}$$

the energy density results from interference

$$I = |E_e + E_p|^2 = E_0^2\exp(-2z/d) + E_1^2 + 2E_0E_1\exp(-z/d)*\cos(ky\sin\alpha + kz). \tag{7}$$

The first term of this expression vanishes rapidly and the second one is constant, so mainly the third term determines the structure of interfence pattern. The resulting interference fringes are inclined against the interface at the angle φ

satisfying the equation

$$\tan\varphi = \frac{\lambda}{\lambda_e} = \frac{\lambda_0}{n_1}\frac{n_1 \sin\alpha}{\lambda_0} = \sin\alpha. \tag{8}$$

As the third term of Eq. (7) includes an exponential factor the contrast of interference fringes dies away with the same constant d as the evanescent wave constant of energy decreases.

If the medium with refraction index n_2 is photosensitive then the energy density (7) can be recorded in it. In this way evenescent wave holograms can be obtained.

3. Experimental set-up and recording of holograms

Let us consider a glass prism, with the refraction index n_g, one face of which is covered with a thin layer of photoresist with the refraction index $n_r (n_r < n_g)$ – see Fig. 2. The hologram resulting from interference of a typical object wave

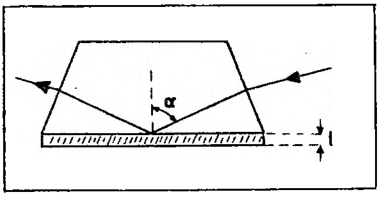


Fig. 2. Total internal reflection in a glass prism at its boundary with optically thinner photosensitive layer. An evanescent field is generated in the layer

with an evenescent one is recorded in the photoresist. The reference wave strikes the photoresist-glass boundary from within the prism at the angle greater than α_c, producing an evanescent field inside the layer. The object wave incident on the photoresist comes from the air.

Such a prism of SF–11 glass ($n_g = 1.825$ for $\lambda_0 = 0.436$ μm and $n_g = 1.777$ for $\lambda_0 = 0.644$ μm) was placed in the experimental set-up shown in Fig. 3. The photoresist AZ 1350 was used to form the layer $l = 0.3$ μm thick. The He-Cd laser ($\lambda_0 = 0.441$ μm) was used as a light source.

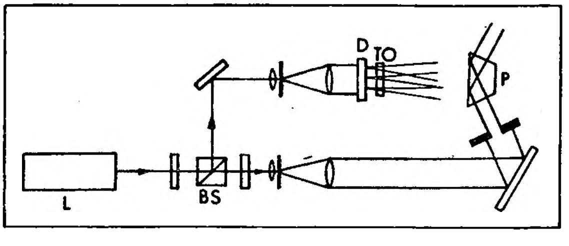


Fig. 3. The experimental set-up for hologram recording. *L* – He-Cd laser, *BS* – beam splitter, *D* – diffuser, *TO* – transparent object, *P* – glass prism with photosensitive layer

The critical angle calculated for total internal reflection of the reference wave was $\alpha_c = 61.85°$. Holograms were recorded for the angle of incidence $\alpha = 62.92°$ chosen experimentally. For this angle a minimum energy density of wave reflected from the boundary (Fig. 12) and a maximum fluorescence of photoresist were observed. The penetration depth for evenescent field was $d = 0.31$ µm. That means that the evanescent wave existed within the whole volume of photoresist. The wavelength of the evanescent wave was $\lambda_e = 0.272$ µm.

4. Reconstruction of holograms and properties of images

The holograms obtained were reconstructed with a He-Cd laser wave its direction of propagation being the same as in the recording process and a reverse one. In the first case two conjugate wave fields (I, II) and in the second one two true fields (III, IV) were reconstructed – see Figs. 4 and 5. Image IV was also observed while reconstructed with the waves incident at angles α different from that of the recording reference wave. Aberrations were not noticed (Fig. 6).

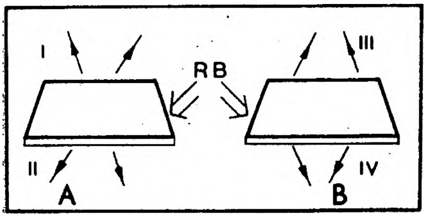


Fig. 4. Hologram reconstruction: *A* – with a beam incident from the same direction as in recording step, *B* – with a beam incident from opposite direction, *RB* – reconstructing beam

Real images were moreover reconstructed with a He-Ne laser beam ($\lambda_0 = 0.633$ µm), incident at various angles. In this case image III was also aberration-free (Fig. 7), but image IV was highly aberrational. These aberrations decreased with the increasing angle of incidence of the reconstructing wave (Figs. 8, 9), that is with the decreasing of the wavelength of the reconstructing evanescent beam (Eq. (3)). The wavelengths of evanescent fields generated by beams of He-Cd and He-Ne lasers incident at various angles are given in Table 1. For He-Cd laser the wavelengths λ_e are slightly different from the

Table 1. Wavelengths of evanescent fields λ_e generated in the photoresist by beams of He-Ne and He-Cd lasers incident at various angles α

Angle of incidence α [^{0}]	61.85	62.92	72.46	80.0	85.0
Beam of the He-Cd laser $\lambda_e^{\text{He-Cd}}$ [µm]	0.274	0.272	0.254	0.246	0.245
Beam of the He-Ne laser $\lambda_e^{\text{He-Ne}}$ [µm]	0.404	0.400	0.374	0.362	0.359

recording one, if compared with those for the He-Ne laser. Then for reconstruction with the He-Ne beam the aberrations should be much greater and they should decrease as the wavelength λ_e approaches the recording one.

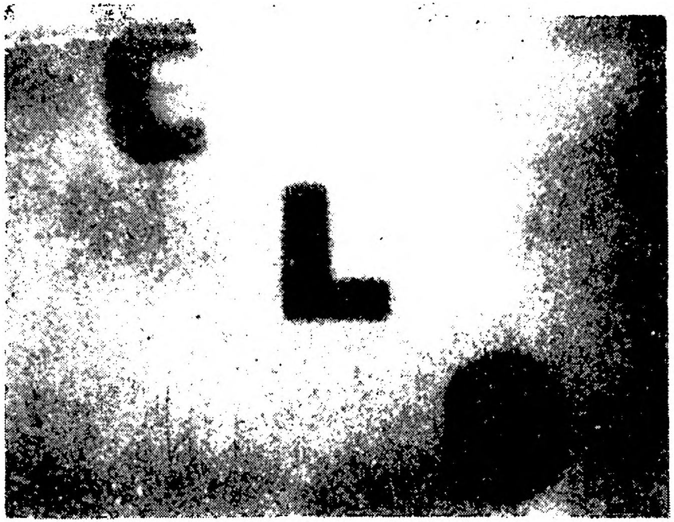
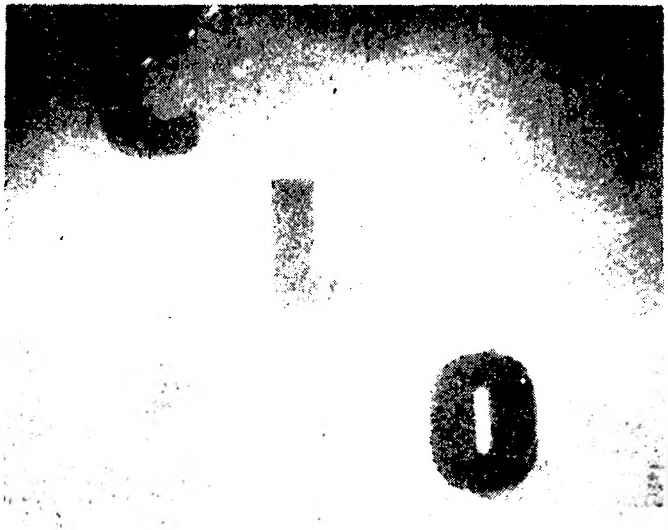


Fig. 5. Reconstruction of image II with a He-Cd laser beam incident at an angle $\alpha = 62.92^0$, i.e., at the angle of incidence of recording reference wave



a

b

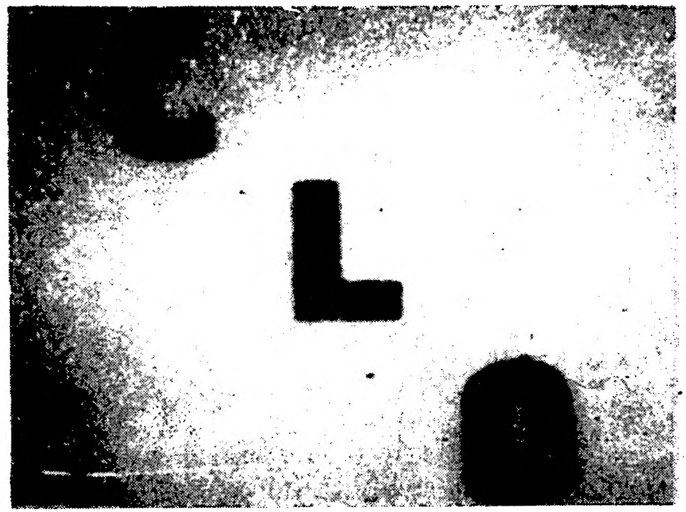


Fig. 6. Image IV reconstructed with a He-Cd laser beam incident at an angle $\alpha = 62.92^0$ (a) and at an angle $\alpha = 59.2^0$, i.e., with a plane wave not an evenescent one (b)

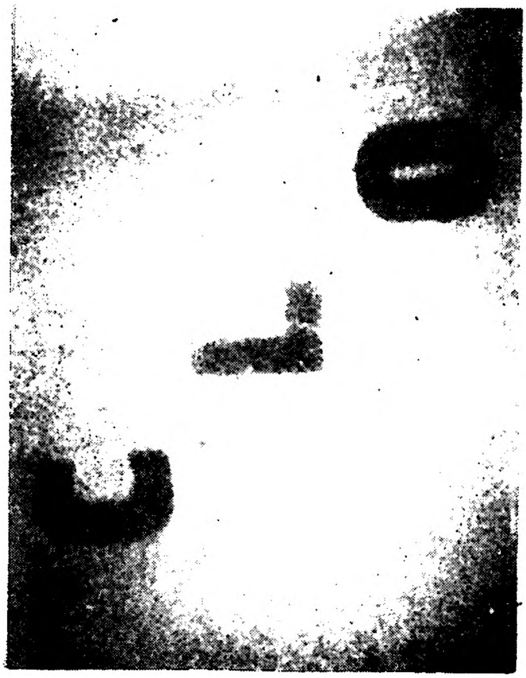


Fig. 7. Reconstruction of an aberration-free image III with a He-Ne laser beam incident at an angle $\alpha = 72.46^0$

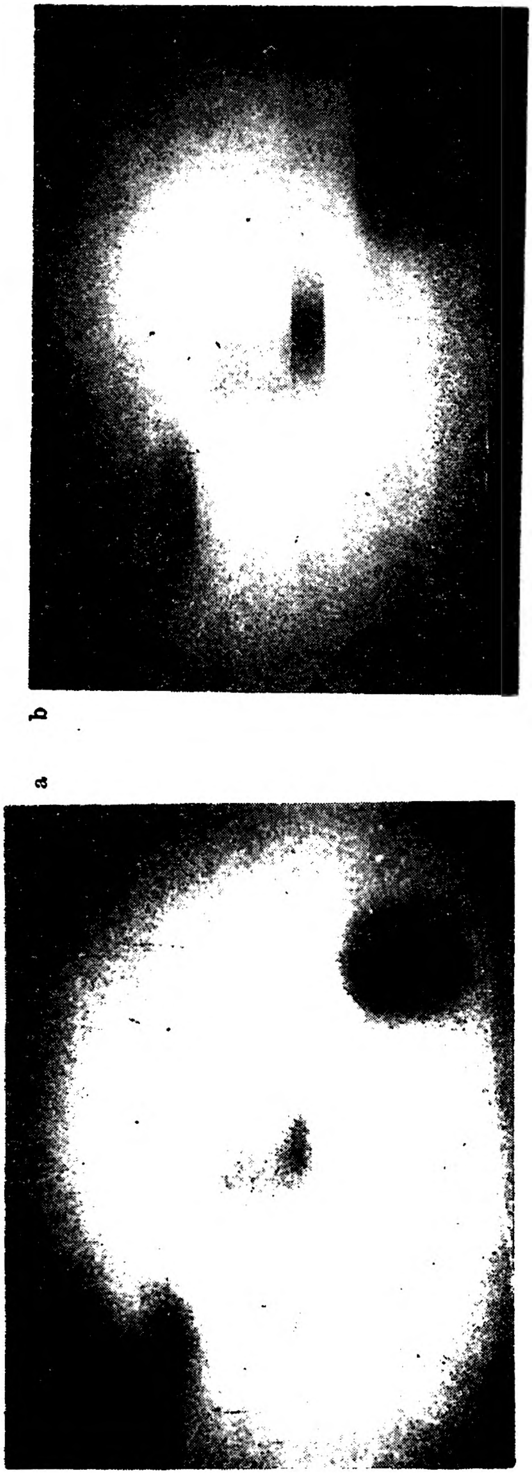


Fig. 8. Image IV reconstructed with a He-Ne laser beam incident at an angle $\alpha = 72.46^0$ (a) astigmatism is visualized by focussing on horizontal lines (b)

The dependence of reconstructed wave direction on the angle of incidence of reconstructing field was also examined (Figs. 10, 11). Angle of diffraction β on the hologram depends on the diffracted wave length. As λ_e for both reconstructing laser beams approaches a constant value for a near 90° then the angle β grows to a constant value too.

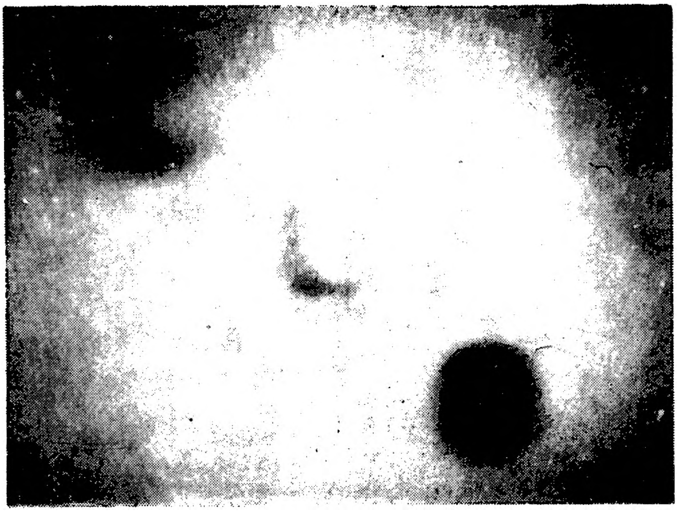


Fig. 9. Image IV reconstructed with a He-Ne laser beam incident at an angle $a = 79.75^0$ – less aberrational

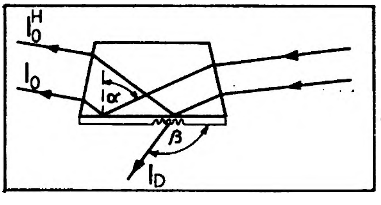


Fig. 10. The experimental set-up for measurements of energy densities and reconstructed wave direction dependences on the angle of incidence of reconstructing wave

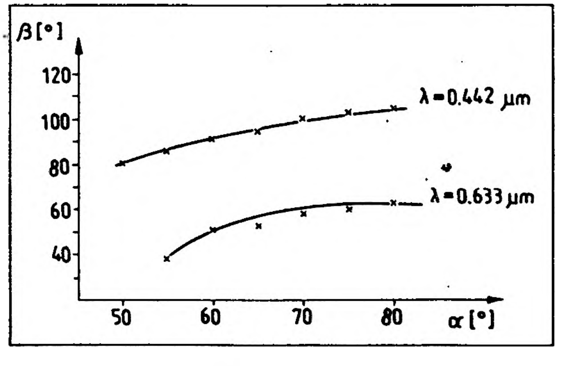


Fig. 11. The angle β of reconstructed wave direction vs. the angle of incidence a of reconstructing beam for reconstruction with He-Cd and He-Ne lasers

Figure 12 displays energy density plots vs. the angle of incidence of reconstructing beam at the photoresist-glass interface. I_0 is the energy density of the beam reflected outside the hologram area (Fig. 10). This energy reaches its minimum in the neighbourhood of the critical angle and then it slowly rises while the energy penetrating the photoresist as an evanescent field decreases. The energy density I_0^H of a beam reflected at the photoresist-glass interface in the hologram area is smaller than I_0, as a part of energy is taken away by the diffracted beam. For large values of α both I_0 and I_0^H approach the same value, when very small fraction of energy of incident wave penetrates into the

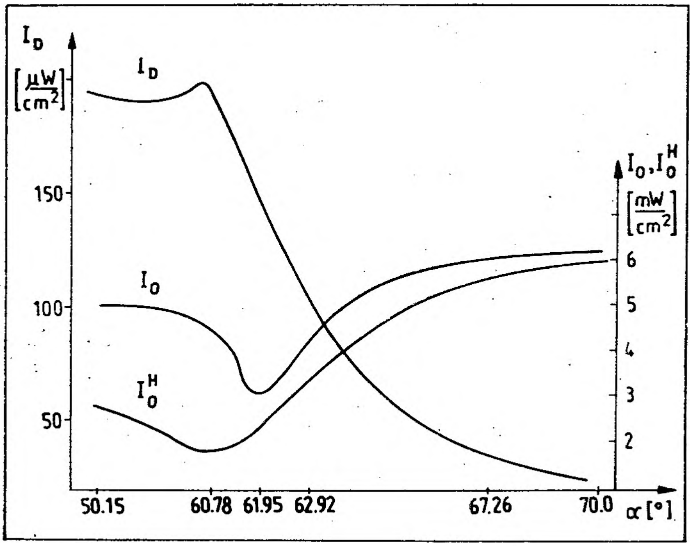


Fig. 12. Energy density vs. angle incidence α of laser beam at the glass-photoresist interface. I_D – energy density of diffracted beam, I_0 – energy density of a beam reflected outside the hologram area, I_0^H – energy density of a beam reflected in the hologram area

photoresist. I_D is the energy density of the diffracted beam, it reaches its maximum near the critical angle and then rapidly decreases as the penetration depth of the evanescent reconstructing wave grows smaller (Eq. (4)). The values of the penetration depth of an evanescent wave generated by a He-Cd laser beam incident at various angles are given in Table 2. For great angles the reconstructing field exists in a small fraction of the hologram volume.

Table 2. Penetration depth of evanescent field generated in photoresist by He-Cd laser beam incident at various angles α

Angle of incidence α [°]	62.92	72.46	80.0
Penetration depth d [μm]	0.311	0.111	0.08

5. Conclusions

Photoresist AZ 1350 proved to be an efficient recording material for evanescent wave holograms. Possibility of forming very thin photoresist films allows to record holograms occupying the whole volume of photosensitive medium. In such a case an absorbing and scattering modulation-free area of recording material does not exist in the neighbourhood of the hologram. The holograms obtained can be reconstructed by waves of different wavelengths. Reconstruction by waves of the same wavelength as the recording beam but incident at different angles does not impose any aberrations.

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Голография с эванесцентной волной отнесения

Описан эксперимент по получению голограмм, фиксирующих эффект классической интерференции изобразительной волны с эванесцентной волной отнесения. Тонкие слои фоторезиста AZ – 1350 представляли собой голографический материал. Эванесцентная волна генерировалась с помощью полного внутреннего отражения на границе резист – стекло. Голограммы восстанавливались при использовании двух светлых волн различной длины. Исследована зависимость качества изображения от условий восстановления.