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Holographic reconstruction of binary microstructures: limitations due to the nonlinearity of the recording material

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ABSTRACT

A method, which makes it possible to evaluate images reconstructed from holograms recorded in nonlinear media was proposed. Nonlinear holographic characteristics (often called as Lin-curves) of the recording material were incorporated in this holographic model. To assess the effects of nonlinear recording in high resolution holography, reconstructed holographic images of binary amplitude microobjects were numerically calculated by this method. Several materials and processings were studied. The calculations suggest that it is possible to optimize the recording parameters. Intensity distributions of reconstructed holographic images of a test object were also measured.

1. INTRODUCTION

Nonlinear characteristics of holographic recording materials can substantially influence the quality of the reconstructed image, especially in holographic optical elements which are to transform the incoming beam(s) into a prescribed spatial intensity distribution with high spatial resolution and fidelity. The greatest part of the papers on nonlinear holographic recording was based on the use of the amplitude transmittance (t) versus exposure (E) curve of the recording material [1-8]. However, the t-E curve is strictly applicable only to thin absorption holograms. The approximate forms of the t-E curves used in these works and the difficulties with the interpretation of the higher order terms in the transmittance of the processed hologram posed further restrictions on the validity of these results. Instead of the t-E curve, the use of the $\sigma(E_0,V)$ curves of the material for the evaluation of the effects of nonlinear recording on the reconstructed holographic image was recently reported [9]. Here σ stands for the square root of the diffraction efficiency of a plane-wave hologram recorded at bias exposure of E_0 and a visibility of V. This method was applied to predict the effect of different developers on the quality of the reconstructed holographic image [10]. The aim of the present contribution is to summarize the results achieved by this method so far and to point out its potential applications.

2. NONLINEAR HOLOGRAPHIC CHARACTERISTICS

It was found [9] that the following analytical function can be fitted to the measured $\sigma(E_0,V)$ curves:

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$$\sigma(E_0,V)=f(E_0)(1-e^{-V})e^{-\frac{[V-V_0(E_0)]^2}{w^2(E_0)}} \tag{1}$$

where E_0 is the bias exposure, V is the visibility of the interference fringes and $f(E_0)$, $V_0(E_0)$ and $w(E_0)$ are parameter functions of the following form:

$$Par(E_0)=c_{i01}\left(\frac{1}{e^{\left(\frac{c_{i11}-E_0}{c_{i12}}\right)}+1}+c_{i13}\right)\left(\frac{1}{e^{\left(\frac{E_0-c_{i21}}{c_{i22}}\right)}+1}+c_{i23}\right)\left(\frac{1}{e^{\left(\frac{c_{i31}-E_0}{c_{i32}}\right)}+1}+c_{i33}\right) \tag{2}$$

where Par stands for f, V_0 and w and c_{ixx} represent the three sets of constants ($i=f, V_0, w$).

A set of experimental $\sigma(E_0,V)$ curves for amplitude holograms recorded in Kodak K649f, taken from Ref. [11] (Chap. 7, Fig. 10.9) is shown in Fig. 1. Theoretical fits by Eq. (1) are also shown. The corresponding set of parameters was published in Ref. [9]. Experimental and fitted $\sigma(E_0,V)$ curves of Agfa-Gevaert 8E75HD [10] in an other representation are shown in Fig. 2.

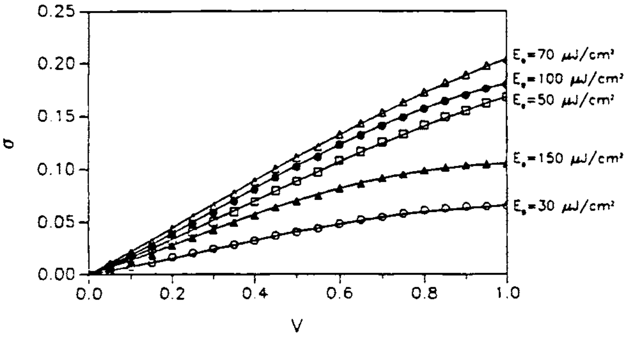

Figure 1 $\sigma(E_0,V)$ function of Kodak K649f. Points: experimental data. Solid lines: Fitted by Eq. (1)

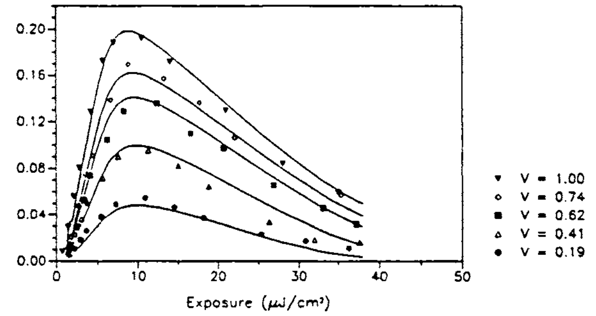

Figure 2 $\sigma(E_0, V)$ function of Agfa-Gevaert 8E75HD. Developer: Pyrogallol. Symbols: experimental data. Lines: Fitted by Eq. (1).

3. EVALUATION OF THE HOLOGRAPHIC IMAGE

According to the method presented in Ref. [9], the complex amplitude of the real image reconstructed from a one dimensional nonlinear hologram can be described by the following equation:

$$\underline{h}(x)=\int_{\xi_1}^{\xi_2}\sigma[E_0(\xi),V(\xi)]\,\underline{M}(\xi)\underline{P}(\xi)\underline{S}^*(\xi)\frac{\cos\rho}{r_2}\exp(ikr_2)\,d\xi \tag{3}$$

where x and ξ are the image and hologram coordinates, r_2 is the separation of the source and observation points (in the hologram and image planes) and ρ is the inclination angle. Here $M(\xi)$, $P(\xi)$ and $S(\xi)$ denote the complex amplitude of the reconstruction, reference and object waves, and * denote complex conjugation.

To investigate the effects of nonlinear hologram recording, a 5-elements Ronchi ruling was assumed as a test object.

Images of such test objects of different linewidth retrieved from holograms recorded in several geometries and materials were calculated by the above method. The examples shown here refer to a ruling of a grating constant of 2 μm.

The length of the one dimensional hologram was 84 mm. The object was centred on the normal of the hologram. The separation of the object and hologram centre was 32 mm. Thus the numeric aperture of the hologram was 0.795. Both the recording and the reconstruction wavelength were 632.8 nm. The quality of the reconstructed image of the Ronchi ruling was described by the following quantities:

1. Contrast of the image, defined as

$$C = \frac{I_{tr}}{I_{op}} \tag{4}$$

where I_{tr} is the integral of the reconstructed intensity over the transparent object lines, while I_{op} that over the opaque ones, including two opaque lines at the edges of the test pattern.

2. Total intensity or brightness (I_T) of the reconstructed image, defined as the integral of the reconstructed intensity along the whole object.

3. Fluctuation of the reconstructed image:

$$\Delta = \sqrt{\frac{\sum_{i=1}^{n}(I_i - I_{av})^2}{n-1}} \tag{5}$$

where I_i is the reconstructed intensity over the ith transparent object line, n the number of transparent object lines and I_{av} the average of the I_i values.

Contrast, brightness and fluctuation as a function of the maximum bias exposure along the hologram at recording is shown for K649f and Agfa-Gevaert 8E75HD in Figs. 3 and 4. The minimum of the beam ratio along the hologram was fixed at R=1. The three quantities cannot be optimized simultaneously, but an image of good quality can be obtained by minimizing Δ.

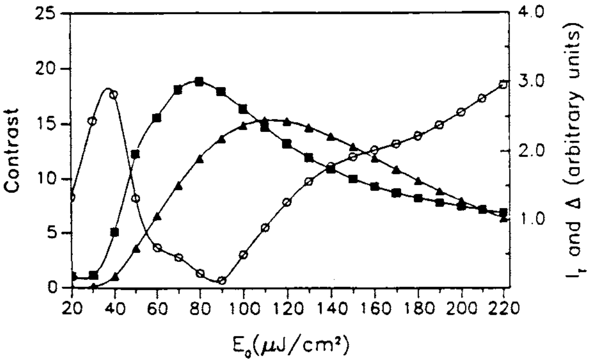

Figure 3 Contrast, brightness and fluctuation of the reconstructed image of the test object *vs.* maximum bias exposure. Kodak 649f, R =1.

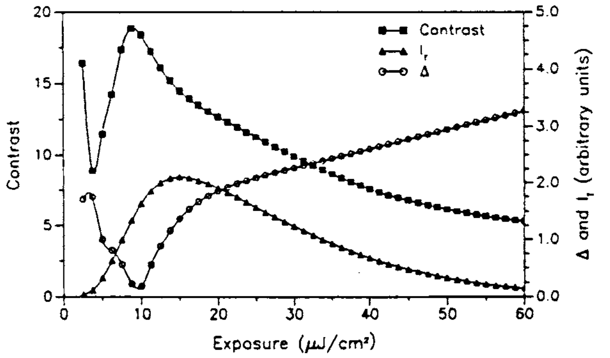

Figure 4 Contrast, brightness (I_T) and fluctuation (Δ) of the reconstructed image of the test object *vs.* maximum bias exposure. 8E75HD, Pyrogallol developer, R=1.

Calculated images reconstructed from holograms recorded in the above geometry in Agfa-Gevaert 8E75HD with different E_0 and R values are shown in Fig. 5.

The images presented in Fig. 5 can be compared to those shown in Fig. 6. These latter curves were measured by microscopic photoelectric scan in an earlier series of experiments. The recording material was also Agfa-Gevaert 8E75HD, but the holograms were developed by Agfa G3P. The recording geometry was the same as assumed in the calculations. The difference in the two measured curves was attributed to the phase errors caused by the uneven glass substrate.

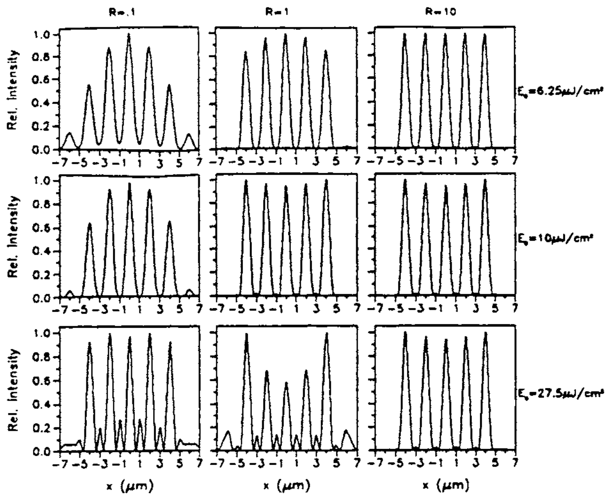

Figure 5 Calculated reconstructed images of the test object. Minimum bias exposure and maximum beam ratio is indicated. 8E75HD, pyrogallol developer.

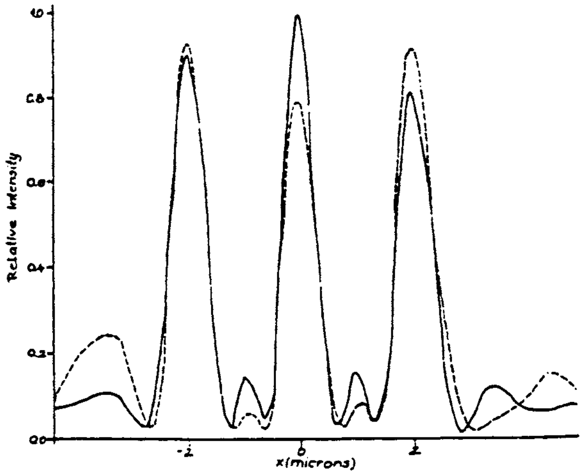

Figure 6 Reconstructed images of a three-line object.The two images were retrieved from holograms recorded in different positions on the same plate. 8E75HD, G3P developer.

4. CONCLUSION

A method was proposed to evaluate nonlinear holographic images retrieved from amplitude holograms. The method was applied to common holographic recording materials (Kodak K649f, Agfa-Gevaert 10E70 and 8E75HD). The calculations showed that holographic recording of non-diffuse microline objects (characterized by the image contrast, brightness and fluctuation) can be optimized by a suitable choice of the bias exposure and beam ratio. The optimal values of these parameters depend strongly on the processing of the hologram and they are different for different types of objects. It is hoped that this method can be applied successfully in designing and copying holographic optical elements. Extension of this method to phase holograms is also planned.

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