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High-efficiency Phase-hologram Gratings

Abstract: Optimum conditions for the generation of high-efficiency hologram gratings are presented. The most efficient phase holograms were obtained for exposures 10 to 20 times larger than those for optimally exposed amplitude holograms. Hologram gratings produced on Agfa Gevaert 8 E 70 recording plates diffracted 40 percent of the incident radiation into the holographic image. This experimentally obtained efficiency is 60 percent of the theoretical maximum for a hologram with a geometric parameter Q of 4.6.

Introduction

For practical applications of holographic methods it is necessary to use high-efficiency holograms that diffract a large portion of the incident radiation into the holographic image. Kodak 649 F and Agfa Gevaert 8 E 70 (8 E 75) plates[1] are commonly used in experimental holographic work.

Amplitude holograms, which alter the amplitude of the reconstructing beam as a function of the spatially modulated amplitude transmittance, give maximum experimental efficiencies of about 5 percent for both recording films.[2–4] Higher efficiencies can be achieved by bleaching the amplitude holograms and making use of the remaining phase-modulating structure. Upatnieks and Leonard,[5] Pennington and Harper[6] and Latta[7] have obtained maximum hologram efficiencies of 30 to 50 percent by bleaching 649 F plates.

We recorded high-efficiency holograms on 8 E 70 plates and investigated the processing and bleaching conditions for optimum exposure. Compared with 649 F plates, 8 E 70 plates have greater sensitivity to He-Ne laser light and thinner emulsion layers.

Recently McMahon and Franklin[8] published investigations on bleached 8 E 70 holograms. They found that high optical quality is much easier to achieve with the thinner 8 E 70 emulsion. Their investigations refer to thick holograms, while ours refer to thicknesses intermediate between thin and thick holograms. Both yielded experimental efficiencies that were the same percentage of the theoretical maximum for the respective values of the geometrical parameter Q [see Equation (1)]. This parameter, as defined by Hargrove,[9] appears in various theories for the diffraction of light by ultrasonic waves.

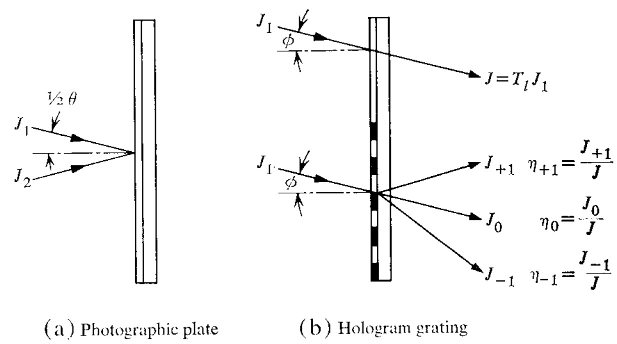

Figure 1 (a) Exposure of hologram gratings J_1, J_2 equals intensities of two interfering beams, θ equals offset angle. (b) Schematic for definition and measurement of hologram efficiencies, η_{+1}, η_{-1}, η_0; ϕ equals angle of incidence of reconstructing beam and T_l equals transmittance of unexposed but processed recording plate.

Theory

It is common for the efficiency of holograms to be studied by means of holographic gratings that are formed by the interference produced by two parallel laser beams incident on the photographic plate at an angle θ [see Fig. 1(a)]. By processing and bleaching the exposed photographic

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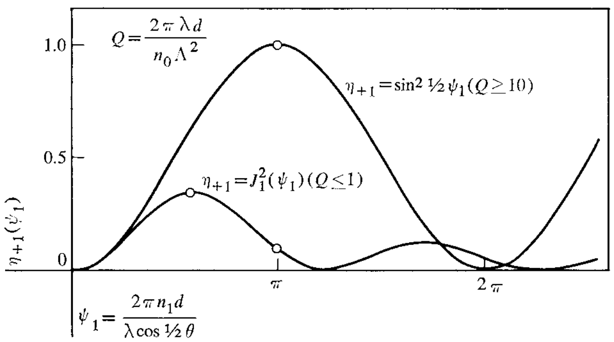


Figure 2 Theoretical hologram efficiency η_{+1} vs phase shift ψ_1 for thin ($Q \leq 1$) and thick ($Q \geq 10$) holograms.

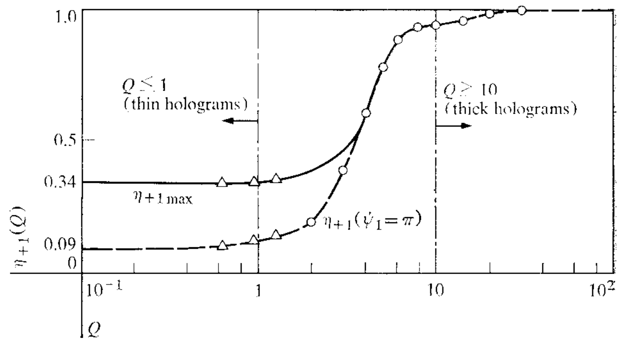


Figure 3 Theoretical maximum hologram efficiency $\eta_{+1\,max}$ (solid line) and efficiency η_{+1} at $\psi_1 = \pi$ (dashed line) vs the parameter Q at Bragg incidence.

Figure 4 H & D curves of Kodak 649 F, Agfa 8 E 70 and 8 E 75 plates processed for gamma values near 2.

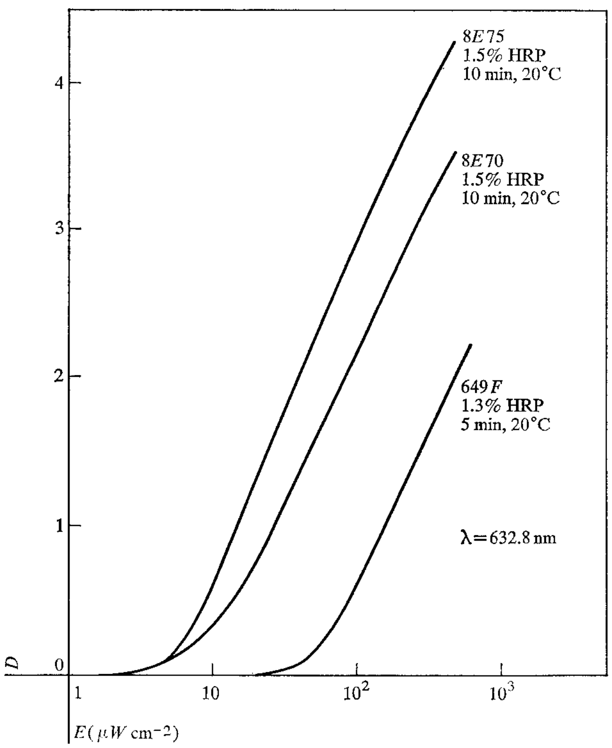


Figure 5 Zero-, first- and second-order efficiency of an R-10-bleached hologram grating vs angle ϕ of reconstructing beam.

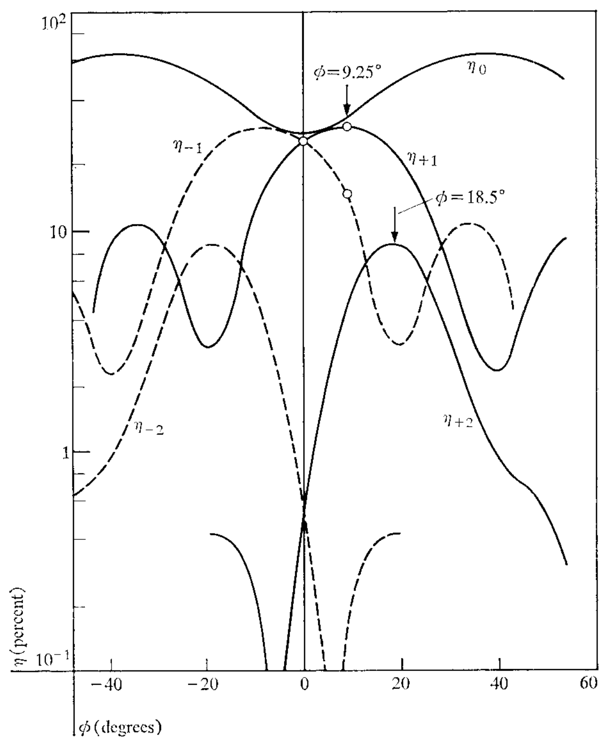


plate one can generate a phase-hologram grating. Hologram efficiencies η_{+1} and η_{-1} are defined as the fraction of reconstructing beam power that is diffracted into the two first-order holographic images [Fig. 1(b)]. In the following discussion this definition is extended to higher-order images, as well as the zero-order response. Thus, the efficiencies used in this paper are defined as $\eta_n = J_n/J (n = 0, \pm 1, \pm 2, \cdots)$, where n is the diffraction order; $J = T_l J_1$ is the normalized reconstructing intensity that takes into account the light losses by surface reflection and by base absorption; and T_l is the transmittance of the unexposed but processed recording plate, which has been measured at 0.88 for Agfa 8 E 70 plates (λ = 633 nm).

The maximum attainable hologram efficiency depends on whether the hologram is a thin or a thick one. We distinguish between thin and thick holograms by using $Q \leq 1$ for thin holograms and $Q \geq 10$ for thick holograms. The parameter Q is defined by

$$Q \equiv 2\pi\lambda d/n_0\Lambda^2, \qquad (1)$$

where λ is the wavelength of the light, d is the emulsion thickness, n_0 is the refractive index of the recording medium and Λ is the grating period.

In a phase grating consisting of a sinusoidal refractive index distribution $n(x) = n_0 + n_1 \cos(2\pi x/\Lambda)$, the theoretical diffraction efficiency is given by simple formulas[10] for both cases $Q \leq 1$ and $Q \geq 10$. The efficiency of thin holograms is described by the square of the first-order Bessel function,

$$\eta_1 = J_1^2(\psi_1), \qquad (2)$$

where ψ_1 is the phase shift introduced by the spatial refractive index of modulation. For thick hologram gratings the coupled-wave theory predicts an efficiency of

$$\eta_1 = \sin^2 \tfrac{1}{2}\psi_1 \qquad (3)$$

for Bragg incidence $\phi = \frac{1}{2}\theta$ of the reconstructing beam. Figure 2 shows the first-order diffraction efficiency plotted as a function of the phase shift $\psi_1 = 2\pi n_1 d/\lambda \cos \frac{1}{2}\theta$ for both hologram types.

Thick hologram efficiencies have a peak at $\psi_1 = \pi$, where the efficiency is 100 percent, while thin holograms have a maximum efficiency of 33.9 percent at $\psi_1 = 0.57$ and an efficiency of only 8.5 percent at $\psi_1 = \pi$. Holograms with values of Q in the range $1 < Q < 10$ have maximum efficiencies ranging from 34 to 100 percent. The theoretical efficiency η_{+1} at $\psi_1 = \pi$ and the maximum obtainable efficiency $\eta_{+1\max}$ are plotted in Fig. 3 as a function of Q. The theoretical values shown in the figure have been taken from Ref. 11 for $Q > 2$ (circles) and from Ref. 9 for $Q =$ 0.62, 0.93 and 1.24 (triangles). The curves for η_{+1} and $\eta_{+1\max}$ are different, since the maximum efficiency for $Q < 4$ occurs at a smaller phase shift ψ_1.

For a useful comparison of experimental results, hologram efficiency studies should always include the hologram parameter Q, which determines the maximum theoretical efficiency.

Experiment

Phase-hologram gratings were produced on Agfa 8 E 70 plates. In all our experiments $\lambda = 633$ nm, $\theta = 18.5°$, $d = 7$ μm, $n_0 = 1.5$ and $\Lambda = 2.0$ μm. These gave a value of $Q = 4.6$. The two interfering beams had equal intensities $J_1 = J_2$, thus generating an interference pattern with a degree of modulation $m = 1$ and an average intensity $J_{dc} = \langle J_1 + J_2 \rangle$. Hologram efficiencies were measured as a function of dc exposure $E = J_{dc}\, t$ by varying the exposure time t.

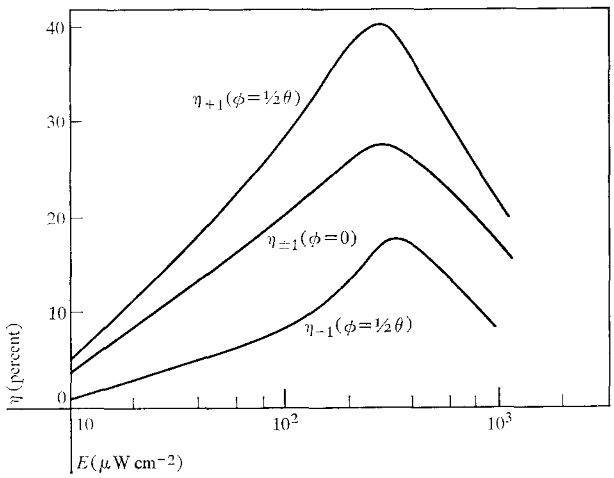


Figure 6 Efficiency η vs exposure E for R-10-bleached 8 E 70 hologram gratings.

All exposed plates were processed in the following way: 10-min development in fresh 1.5 percent Kodak HRP developer, 1-min stop bath, 4-min fix in Agfa G 334, 20-min wash in water, 5-min bleach in R-10 bleach[13] or 12-min in Kodak EB-2 bleach or 5-min in potassium ferricyanide (PF) bleach,[14] 10-min wash in water, 1-min in 30%, 60% and 90% ethanol, and drying in an anhydrator box. To obtain reproducible results the temperatures of developer and bleach baths were kept at (20 ± 0.1)°C. With these processing parameters the unbleached 8 E 70 emulsion had a low gamma-value of about 2 in the linear part of the H & D curve (Fig. 4).[12]

We found that the hologram efficiency was influenced by the bleaching time. When we increased the bleaching time (using R-10 bleach) from 1.5 to 5 min, the maximum obtainable efficiency was increased and occurred at lower exposure values. However, bleaching times longer than 5 min did not cause the efficiency to increase further. We also investigated the effect of prehardening the emulsions in an SH-5 solution prior to development.

Results

The efficiency of a recorded phase-hologram grating depends strongly on the angle of incidence ϕ of the reconstructing beam. Figure 5 shows this angular dependence for the zero, first and second diffraction orders. The first-order efficiency has its maximum for Bragg incidence $\phi = \frac{1}{2}\theta = 9.25°$. The three circles in Fig. 5 indicate, respectively, the efficiencies $\eta_{\pm1}$ for normal incidence ($\phi = 0$) and η_{+1} and η_{-1} for the Bragg angle ($\phi = \frac{1}{2}\theta$). These efficiencies are plotted as functions of exposure in Fig. 6 for R-10-bleached hologram gratings. All three efficiencies increase with increasing exposure, achieve a maximum value and then decrease. This behavior agrees

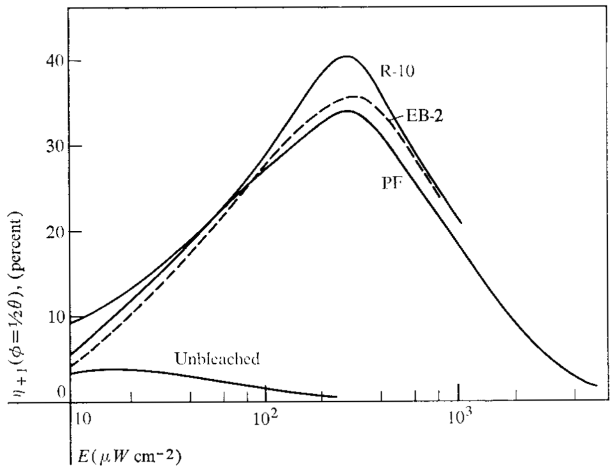
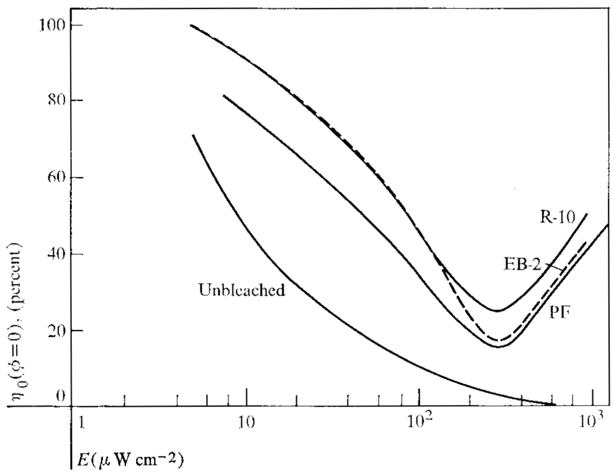


Figure 7 First-order efficiency η_{+1} of unbleached and R-10-, EB-2- and potassium ferricyanide-bleached 8 E 70 hologram gratings at Bragg incidence, $\phi = \frac{1}{2}\theta$, as functions of exposure E. EB-2 bleaching caused stripping of the not-prehardened emulsion. The dashed EB-2 curve is the efficiency of unstripped parts of the hologram grating.

Figure 8 Zero-order efficiency η_0 of not-prehardened unbleached and bleached 8 E 70 hologram gratings at normal incidence $\phi = 0$, plotted as function of exposure E.



qualitatively with the theoretical prediction shown in Fig. 2, indicating that with increasing exposure the phase shift ψ_1 becomes larger. In Fig. 7 the Bragg-angle efficiencies η_{+1} of three bleaches are compared with the efficiency of unbleached holograms. A maximum efficiency of 40 percent was obtained for R-10 bleached holograms. This value is higher than the theoretical value of 33.9 percent for thin holograms. The three bleaches investigated produced maximum efficiencies if the holograms were exposed to 200 to 300 μW cm^{-2}. Such exposures are 10

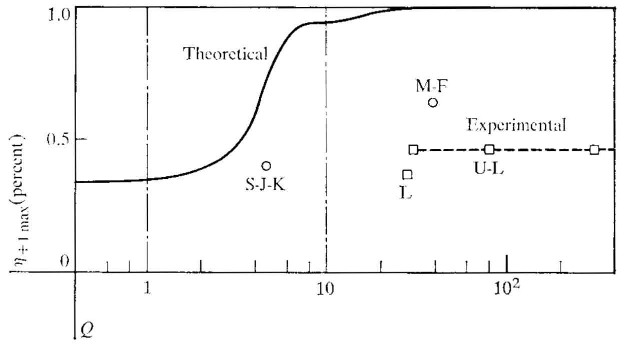
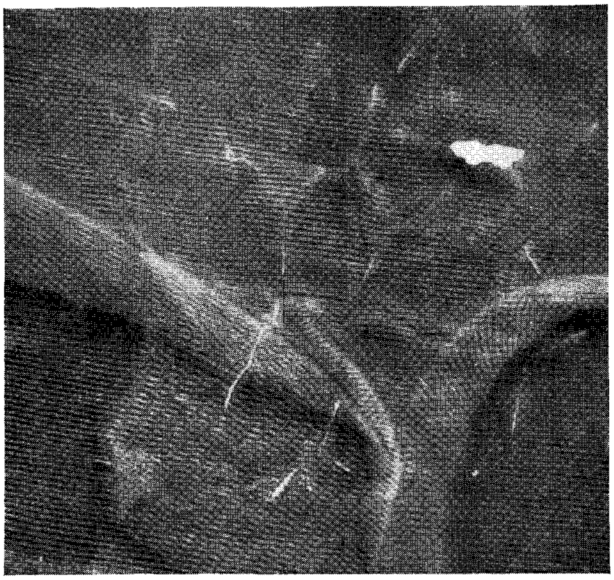


Figure 9 Experimental maximum efficiencies η_{+1} of hologram gratings recorded on 8 E 70 plates (circles) and 649 F plates (squares), compared with theoretical values for different values of Q. M-F = McMahon and Franklin; U-L = Upatnieks and Leonard (including losses due to reflection and base absorption); L = Latta. S-J-K = the present authors.

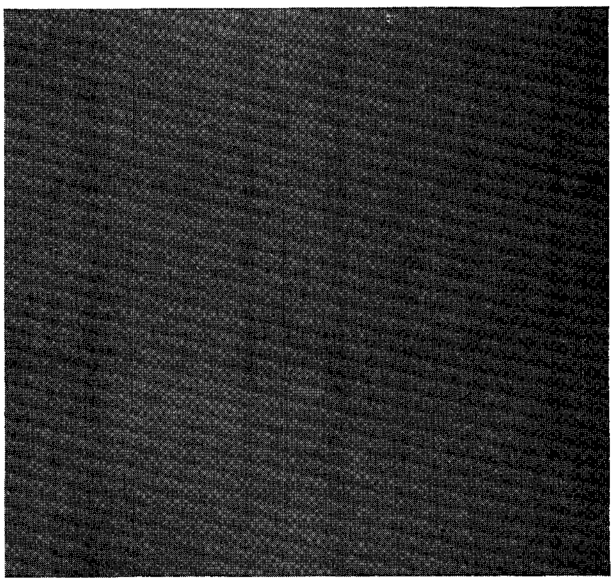
to 20 times larger than those required for optimally exposed amplitude holograms. The curves for the zero-order (undiffracted light) efficiency η_0 as a function of exposure show a minimum intensity at the exposure for which first-order diffraction efficiency has its maximum. This behavior (Fig. 8) also compares with theoretical predictions.[10,11]

The angular dependence and the maximum efficiency of 40 percent obtained in the experiments indicate that the holograms we investigated have a behavior intermediate between those of thin and thick holograms. This observation coincides with the fact that the hologram parameter Q had a value of 4.6, (see Fig. 3). In Fig. 9 our experimental results are compared with those of McMahon and Franklin[8] for 8 E 70 plates, and with those of Upatnieks and Leonard[5] and Latta[7] for 649 F plates. The results for 8 E 70 plates show that about 60 percent of the theoretical maximum efficiency was achieved in our experiment for $Q = 4.6$ and in that of McMahon and Franklin for $Q = 39$.

Figures 5 through 8 refer to efficiencies of hologram gratings obtained with not-prehardened 8 E 70 emulsions. R-10- and ferricyanide-bleached holograms gave perfect grating qualities. However, EB-2 bleaching (dashed curves in Figs. 7 and 8) caused stripping of the emulsion due to the attack of peroxide. The different surface quality is demonstrated in Fig. 10, which shows two scanning electron microscope photographs of EB-2- and R-10-bleached 8 E 70 hologram surfaces with grating periods Λ of 2 μm each. More information about the R-10-bleached hologram surface can be taken from Fig. 11 which shows the same grating at higher magnification. The three-dimensional structure of the surface becomes visible at the purposely scratched parts of the grating. This photograph proves that the R-10-bleaching process produces not only a refractive index grating, but also a relief structure with a



EB-2



R-10

Figure 10 Scanning electron microscope photographs of EB-2- and R-10-bleached hologram gratings with grating periods $\Lambda = 2$ μm. Because of peroxide attack, EB-2-bleached holograms on not-prehardened 8 E 70 emulsions show stripping of the emulsion.

periodically varying emulsion thickness due to the tanning action of the reaction products.

Pennington and Harper[6] have shown that surface-ripple increases the noise in reconstructed images, especially in the case of diffuse holograms. Hologram gratings, however, produce less noise than general holograms, since there exist no intermodulation terms and since the surface relief has the same spatial frequency as the refractive index grating.

Figure 11 Scanning electron microscope photograph of the emulsion surface of R-10-bleached hologram gratings. The scratch tracks indicate spatially modulated surface deformations with a period of 2 μm.

It is known that prehardening removes the tendency toward formation of a surface grating. Pennington and Harper[6] reported that 10 min. prehardening of Kodak 649 F plates in SH-5 prehardening solution was necessary before stripping of EB-2 bleached plates was negligible. We found that Agfa 8 E 70 require a 25 min. prehardening in SH-5 bath to prevent stripping of EB-2-bleached emulsions. By prehardening, the efficiency maximum was shifted to higher exposure values and was slightly reduced due to the reduction of the surface relief. EB-2-bleached hologram gratings that were prehardened for 25 min. gave an efficiency of 35 percent, instead of 36 percent obtained without prehardening. R-10-bleached plates had 40 percent efficiency without prehardening, 37 percent with 10 min. prehardening and 34 percent with 25 min. prehardening.

Conclusions

We have shown that high-efficiency holograms can be generated by bleaching Agfa 8 E 70 plates. The phase holograms were recorded under conditions giving a value of 4.6 for the geometrical parameter Q. Thus, they were neither the typical thin nor the typical thick holograms, but were of an intermediate type. Kodak R-10 bleach resulted in the highest diffraction efficiencies. Maximum efficiency was achieved for Bragg incidence of the reconstructing beam and for hologram exposures 10 to 20 times larger than those for optimally exposed amplitude holograms. The measured maximum efficiency, $\eta_{+1} = 40$

percent, is about 60 percent of the maximum theoretical value for $Q = 4.6$. Higher absolute efficiencies have been obtained for thick holograms.[8] Therefore, the experimental setup for recording high-efficiency holograms of an object must ensure that $Q \geq 10$ over the entire hologram for all object points. Furthermore, the exposed holograms should be processed for a low gamma-value. The less-active R-10 and potassium ferricyanide bleaches should be preferred for bleaching 8 E 70 emulsions.

Acknowledgments

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References and notes

1. Formerly there were 8 E 70 and 8 E 75 plates which were sensitized for 633 nm and 690 nm, respectively. Now there is a new plate, called 8 E 75, which is sensitized for both wavelengths. In this paper the ambiguous designation 8 E 75 refers to the new plate.
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