Diffraction efficiency and signal-to-noise ratio of diffuse-object holograms in real time in polyvinyl alcohol photopolymers

Celia García, Inmaculada Pascual, and Antonio Fimia

We studied the influence of the beam ratio and intensity on the optical quality of the transmission hologram images of diffuse objects stored in a photopolymer and reconstructed in real time. The signal-to-noise ratio and the diffraction efficiency were used as measures of the optical quality. We obtained a signal-to-noise ratio of 0.94 with a diffraction efficiency of 13% for a beam ratio of 20 and an intensity of 1.2 mW/cm^2.

OCIS codes: 160.5470, 110.4280, 160.2900.

1. Introduction

In recent years, many types of photopolymerizable systems have been developed as materials for recording holograms.[1] These materials have many characteristics, such as good energetic and spectral sensitivity, high resolution, high diffraction efficiency, temporal stability, and processing in real time, which make them suitable for recording holograms. All these characteristics mean that such materials are useful in applications such as holographic optical storage, production of holographic optical elements, and holographic interferometry.[2,3]

Despite the fact that many systems of this type have been developed, few studies are to be found that relate to the measurement of the optical quality of transmission holograms of diffuse objects and noise sources that reduce the quality of these images.[4,5] In fact, the study carried out by Ingwall and Fielding[4] was the first to present findings relating to the signal-to-noise ratio of diffuse objects stored in photopolymers.

In this paper we study the influence of the beam ratio and intensity on the signal-to-noise ratio and diffraction efficiency in diffuse-object holograms stored in a photopolymer and reconstructed in real time.

2. Experiment

The photopolymer used in our experiment is based on acrylamides.[6] The photopolymerizable system used consisted of acrylamide as a monomer, triethanolamine as a radical generator, and Eosin Yellowish as a sensitizer. All the components were supported in a film of polyvinyl alcohol. The photosensitive aqueous solution was prepared by addition of 1.5 ml of 8 g/l Eosin Yellowish, and 8 ml of a solution of 2.5 M of acrylamide and 1.5 M of trietanolamine to 50 ml of polyvinyl alcohol (10% by weight). The film was prepared by means of coating a 20 cm × 40 cm glass plate with the photosensitive solution and then allowing it to dry for 24 h under normal conditions [T, ≈21–23 °C; relative humidity, ≈40–60%]. The resulting thickness of the film was 70 ± 5 μm. Finally, we cut the 20 cm × 40 cm glass plate into plates measuring 6.5 cm × 6.5 cm to use in our experimental setup.

The behavior of this photopolymer when holographic gratings with a spatial frequency of 1000 lines/mm were stored is shown in Fig. 1. The holographic gratings were recorded with an argon laser emitting at 514 nm with an intensity of 1.2 mW/cm^2. The reconstruction of the hologram was made at the Bragg angle with a He–Ne laser tuned to 633 nm. The evolution of the diffracted intensity of this beam as a function of time was monitored in real time. The maximum diffraction efficiency achieved was ~65% with an energetic sensitivity of 200 mJ/cm^2.

C. García (celia@aclis2.disc.au.es) and I. Pascual are with the Laboratorio de Óptica, Departamento Interuniversitario de Óptica, Universidad de Alicante, Apartado 99, Alicante 03080, Spain. A. Fimia is with the Departamento de Ciencias Experimentales y Tecnología, División de Óptica, Universidad Miguel Hernández, Campus de Elche, Edf. La Galia, Avda del Ferrocarril, s/n, Alicante 03202, Spain.

Received 2 February 1999; revised manuscript received 27 May 1999.

0003-6935/99/265548-04$15.00/0

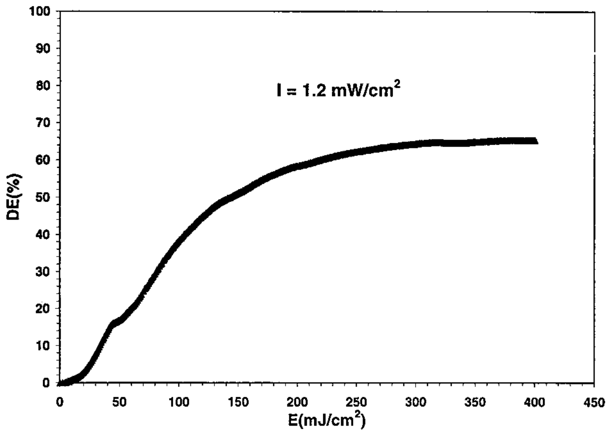

Fig. 1. Diffraction efficiency (DE) as a function of exposure for $I = 1.2\ \mathrm{mW/cm^2}$.

The experimental setup used to obtain diffuse-object holograms is shown in Fig. 2. Both recording and reconstruction of the hologram were performed with a 5-W argon laser emitting at 514 nm.

The diffuse object used was a test target in front of which was placed a diffusor. Only the zone corresponding to 1.6 lines/mm was stored. The virtual image situated in the object plane was focalized by the lens L_2 and captured by a CCD camera.

The holographic images were captured in real time with a frequency of 10 s. To evaluate the optical quality of these images, we used the signal-to-noise ratio [Eq. (1)] and diffraction efficiency [Eq. (4)], defined as

$$\mathrm{SNR} = I_{\max}/I_{\min}, \tag{1}$$

where $I_{\max}$ [Eq. (2)] and $I_{\min}$ [Eq. (3)] are given by

$$I_{\max} = \overline{I_1} \qquad \text{with } I_1 = \sum_{j=1}^{128}\left(\sum_{p=1}^{5}\sum_{i=N_{2p}}^{N_{2P+1}} I_{ij}\right), \tag{2}$$

$$I_{\min} = \overline{I_2} \qquad \text{with } I_2 = \sum_{j=1}^{128}\left(\sum_{p=0}^{5}\sum_{i=N_{2p+1}}^{N_{2P+2}} I_{ij}\right), \tag{3}$$

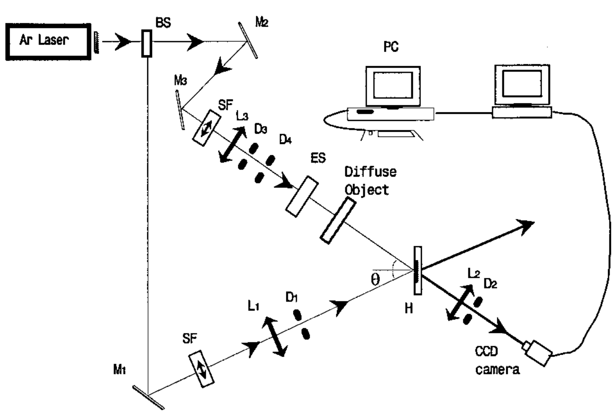

Fig. 2. Experimental setup: BS, beam splitter; M, mirrors; SF, spatial filter; L, Lens; D, diaphragm; ES, electronic shutter; H, holographic plate.

so that

$$\sum_{p=0}^{5} (N_{2p+1} + N_{2p+2}) = 128,$$

where I_{ij} is the intensity of the pixel in the position i, j and N_i marks the beginning and the end of each of the fringes.

Since the signal-to-noise ratio of the object image depends on both the total incident intensity and the beam ratio, all signal-to-noise measurements have been normalized with respect to the signal-to-noise ratio of the object given by Eq. (1).

The diffraction efficiency was calculated from the image captured by the CCD camera:

$$\mathrm{DE} = (I_d/I_i)100 \tag{4}$$

with

$$I_d = \sum_{i=1}^{128}\sum_{j=1}^{128} I_{ij}, \qquad I_i = KI_o = K\sum_{i=1}^{128}\sum_{j=1}^{128} I_{o_{ij}}, \tag{5}$$

where I_d is the diffracted intensity captured by the CCD, I_o is the intensity of the object beam, I_i is the incident intensity, and K is the beam ratio.

3. Discussion

As we indicated above, the photopolymer used to store the diffuse object hologram is a material whose response depends on the intensity and the beam ratio. For this reason we studied its behavior, using different intensities and beam ratios.

The results obtained for a constant beam ratio, $K = 5$, and different total incident intensities, $I = (0.6, 1.2, 2.4, 4.8)\ \mathrm{mW/cm^2}$, are shown (Fig. 3).

Figure 3 shows the normalized signal-to-noise ratio as a function of time [Fig. 3(a)] and diffraction efficiency [Fig. 3(b)]. In both figures the curves corresponding to different total incident intensities from $I = 0.6\ \mathrm{mW/cm^2}$ to $4.8\ \mathrm{mW/cm^2}$ are shown.

In Fig. 3(a) it can be seen that for low intensities ($I = 0.6\ \mathrm{mW/cm^2}$ and $I = 1.2\ \mathrm{mW/cm^2}$) the signal-to-noise ratio reaches a maximum value and then remains stable. When the intensity is increased ($I = 2.4\ \mathrm{mW/cm^2}$ and $I = 4.8\ \mathrm{mW/cm^2}$), it reaches a maximum value and then, above certain periods of time, decreases. In other words, the noise takes longer to be stored. This is due to the beam ratio that exists between the different waves that make up the noise and the total intensity. If the intensity affects the object signal, it will, for the same reason, affect the noise, since this is stored in the form of gratings with a frequency different from that of the object itself. When the intensity is increased, the maximum signal-to-noise ratio increases and the slope of the first part of the graph is greater. In other words, the velocity of polymerization increases, and the hologram is formed more quickly.

Figure 3(b) shows the signal-to-noise ratio as a function of diffraction efficiency. For all the total incident intensities, the shape of the curve is the same and the signal-to-noise ratio increases until it

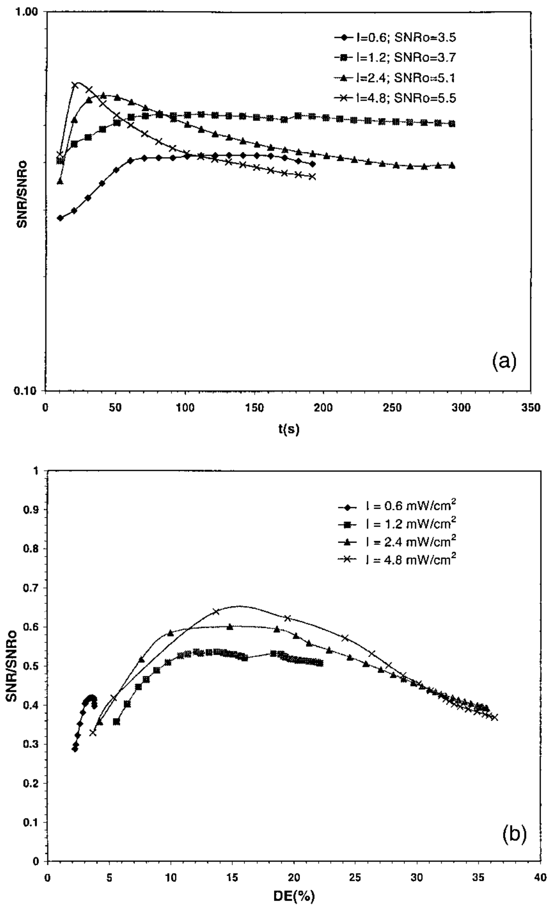

Fig. 3. (a) Normalized signal-to-noise ratio (SNR) as a function of time for $K = 5$ and $I = (0.6, 1.2, 2.4, 4.8)$ mW/cm^2. (b) Normalized signal-to-noise ratio as a function of diffraction efficiency for $K = 5$ and $I = (0.6, 1.2, 2.4, 4.8)$ mW/cm^2.

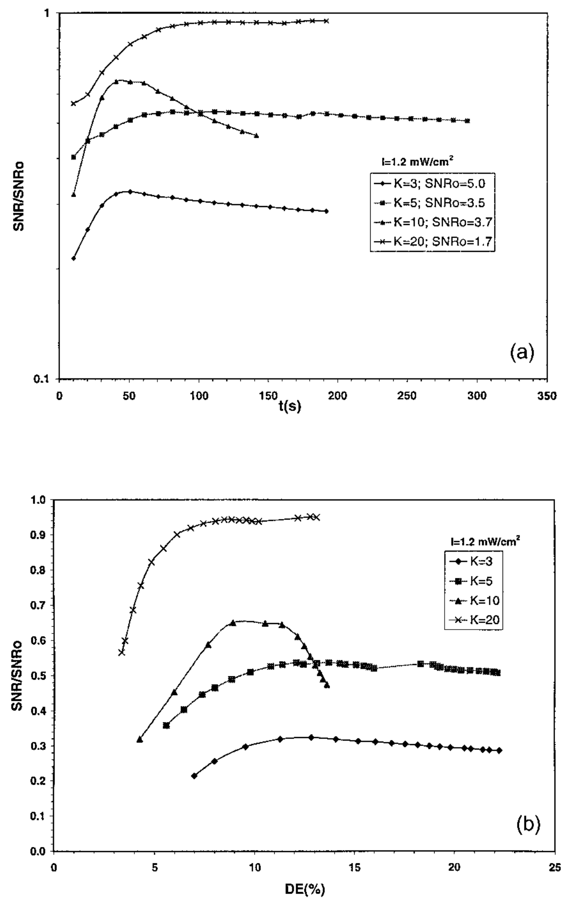

Fig. 4. (a) Normalized signal-to-noise ratio (SNR) as a function of time for $I = 1.2$ mW/cm^2 and $K = (3, 5, 10, 20)$. (b) Normalized signal-to-noise ratio as a function of diffraction efficiency for $I = 1.2$ mW/cm^2 and $K = (3, 5, 10, 20)$.

reaches a maximum and then decreases. When $I = 0.6$ mW/cm^2, low diffraction efficiencies are obtained. With this intensity the material hardly responds at all, and, since there is no difference between the values of I_{max} and I_{min}, we can say that only the CCD noise[7] is stored at this intensity. When the intensity is increased ($I = 1.2$ mW/cm^2, $I = 2.4$ mW/cm^2, and $I = 4.8$ mW/cm^2), higher diffraction efficiencies are obtained.

In this way we can determine the signal-to-noise ratio that can be achieved and the efficiency with which the images are obtained. If we use an intensity of $I = 2.4$ mW/cm^2, the maximum signal-to-noise ratio will be ~0.6 and the diffraction efficiency of the stored images will vary between 10% and 20%. However, if we use an intensity of $I = 4.8$ mW/cm^2, the maximum signal-to-noise ratio will be ~0.65 and the diffraction efficiency between 14% and 17%.

We can say that the curves of SNR/SNR_0 against diffraction efficiency are optimization curves and directly indicate the area to work within if we want to achieve a particular signal-to-noise ratio. They also indicate the range of diffraction efficiencies of the stored images.

From the above it can be seen that the photopolymer used in our study is a material whose response depends on the intensity.

We also studied the influence of the beam ratio on the quality of the holographic image. The beam ratios analyzed were $K = (3, 5, 10, 20)$, for a constant intensity, $I = 1.2$ mW/cm^2 (Fig. 4). Figure 4 shows the normalized signal-to-noise ratio as a function of time [Fig. 4(a)] and diffraction efficiency [Fig. 4(b)]. In this case the curves in the figures correspond to different beam ratios varying from $K = 3$ to $K = 20$.

In Fig. 4(a) it can be seen that when the beam ratio is increased the maximum signal-to-noise ratio obtained increases. The best results were obtained for $K = 20$ with a signal-to-noise ratio of 0.94, giving a holographic image with a signal-to-noise ratio similar to that of the object image captured.

Figure 4(b) shows the normalized signal-to-noise ratio as a function of the diffraction efficiency for different beam ratios. This graph shows the diffraction efficiencies that may be reached when the image of the diffuse object is stored and, at the same time, the signal-to-noise ratio.

It can be seen that, when the beam ratio decreases, higher diffraction efficiencies are obtained, but the signal-to-noise ratios are lower. These experimental results are similar to those obtained previously for photographic emulsions.[8] No linear relationship between signal-to-noise and beam ratios was found. For low values of K, $K = 3$ and $K = 5$, the maximum values of the signal-to-noise ratio obtained are 0.3 and 0.5, respectively, with diffraction efficiencies of between 10% and 25%. To obtain higher values of signal-to-noise ratio, higher beam ratios, $K = 10$ and $K = 20$, must be used, but in this case the diffraction efficiency is reduced.

From the graph it can be seen that for this intensity the highest signal-to-noise ratio of 0.94 and diffraction efficiency of 13% are obtained when $K = 20$.

4. Conclusions

The experimental results presented in this paper indicate that the signal-to-noise ratio depends on the intensity and on the beam ratio. The signal-to-noise ratio increases when the beam ratio and the intensity increase, but the diffraction efficiency does not. In conclusion, the behavior of diffuse-object holograms in real-time polyvinyl alcohol photopolymers has been presented, showing the influence of the intensity and the beam ratio. The best results were obtained for a beam ratio of 20 and an intensity of 1.2 mW/cm^2, with a signal-to-noise ratio of 0.94 and an efficiency of 13%.

Finally, it should be noted that the signal-to-noise ratio of diffuse objects is a relative parameter that can be compared only in similar diffuse objects. However, in our study we normalized the signal-to-noise ratio, making it independent of the object and thus enabling us to determine the behavior of the material itself.

Another question involves the response of the material. A minimum intensity is needed to enable the hologram to be stored. For $I = 0.6\ mW/cm^2$ we can say that only the CCD noise is stored. The holographic images are stored, starting from $I = 1.2\ mW/cm^2$. However, the storage of information is quicker when the intensity used is increased.

These results show that it is possible to obtain diffuse-object holograms, of good optical quality, in real time in photopolymers.

This study was financed by the Comisión Interministerial de Ciencia y Tecnología of Spain (project MAT 97-0705-C02-02).

References

1. R. A. Lessard, R. Changkakoti, and G. Manivannan, “Holographic recording materials,” Opt. Mem. Neural Netw. **1,** 307–369 (1992).
2. K. Curtis and D. Psaltis, “Recording of multiple holograms in photopolymer films,” Appl. Opt. **31,** 7425–7428 (1992).
3. S. Martin, C. A. Feeley, and V. Toal, “Holographic recording characteristics of an acrylamide-based photopolymer,” Appl. Opt. **36,** 5757–5768 (1997).
4. R. T. Ingwall and H. L. Fielding, “Hologram recording a new Polaroid photopolymer system,” in *Applications of Holography*, L. Huff, ed., Proc. SPIE **523,** 306–312 (1985).
5. C. García, I. Pascual, and A. Fimia, “Contrast of diffuse object holograms in PVA-acrylamide photopolymers: real time measurements,” in *Holographic Materials V*, T. Trout, ed., Proc. SPIE **3638,** 113–118 (1999).
6. S. Blaya, L. Carretero, R. Mallavia, A. Fimia, R. F. Madrigal, M. Ulibarrena, and D. Levy, “Optimization of an acrylamide-based dry film used for holographic recording,” Appl. Opt. **37,** 7604–7610 (1998).
7. Gerald C. Host, *CCD Arrays, Cameras and Displays*, 2nd ed. (Society of Photo-Optical Instrumentation Engineers, Bellingham, Wash., 1998).
8. A. Fimia, R. Fuentes, and A. Beléndez, “Diffuse-object holograms in silver halide emulsions: influence of the beam ratio on the efficiency and the signal-to-noise ratio,” Appl. Opt. **35,** 782–786 (1996).