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SPATIAL FREQUENCY MULTIPLEXED DIFFUSE-OBJECT HOLOGRAMS OF N OBJECT WAVES RECORDED IN BLEACHED SILVER-HALIDE EMULSIONS

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ABSTRACT

In several important applications of holography such as optical information storage it is necessary to multiplex several functions or many optical components in the same thin film recording material. An optically recorded multiple grating hologram can be encoded either sequentially or simultaneously, but for the same total exposure, the diffraction efficiency of sequentially recorded holograms is lower than for a simultaneous hologram. If the number of multiplexed gratings is increased, and the angles between these gratings are reduced, the recorded object beam should resemble the field from a diffuse-object. However, in actual holograms, noise is present and it seriously limits that density. That is why maximun storage density is a function of the hologram's signal-to-noise ratio (SNR). For all of these reasons it is important to analyze the characteristics of diffuse-object holograms in the field of information storage. In this communicaction we present experimental results on the influence of the number of object waves and their spatial distribution on diffraction efficiency and SNR for bleached holograms recorded by using a collimated reference wave and N divergent object waves. The N object waves are interfered with the reference wave by using a simultaneous recording (coherent recording).

KEY WORDS: Holography, holographic recording materials, diffuse-object holograms, bleached emulsions.

1 . INTRODUCTION

The storage of a great number of object waves is required for the design of both holographic memories and holographic optical interconnects. The problems related to noise that come up during recording and reconstruction of these devices are quite similar and can be analyzed in order to improve the image quality that these optical systems provide. Noise also seriously limits storage density, which is why maximum storage density is a function of the hologram's signal-to-noise ratio (SNR)[1]. Volume phase holograms are attractive for use as optical elements or for holographic storage due to their large potential efficiency and information densities. Several materials are available for holographic storage. One of the most common materials is photographic emulsion. Bleached silver halide emulsions have long been used as a medium for recording volume phase holograms because they offer several attractive advantages[2]. These advantages include a relatively high sensitivity, ease of processing, improved processing chemistries and high efficiency. Unfortunately, while the resulting phase holograms have high diffraction efficiency, this is usually accompanied by an increase in the noise and a consequent reduction in image quality[3,4].

In this communication we will experimentally analyze noise in cases in which a large number of coherently shaped object waves are stored in a phase recording material in a way that allows us to obtain information about the relationship that exists between the recording material, the number of waves that are being stored and the spectral distribution of the object waves. Holograms were recorded using a collimated reference wave and N divergent object waves. The N object waves are made to interfere with the reference wave through simultaneous recording (coherent recording). The experimental results obtained are compared with the results obtained for diffuse object holograms. The study is of particular importance for the use of thick holograms in optical storage when a great number of object waves must be stored in a volume hologram.

2 . EXPERIMENTAL RESULTS

In order to analyze the influence of the number of object waves on the characteristics of diffuse object phase holograms, we use a series of objects that when illuminated by transmission, give rise to specific or almost specific sources. These are

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situated in a very orderly way, almost like a matrix, so that the emerging wave from each specific source can be considered an object wave. By varying the distance between the dots we can vary the number of object waves. The experimental set-up used in our experiments is shown in Figures 1 and 2. The matrices were pasted onto a plate of diffusing glass. Some of the objects had an opaque zone in the center, and others did not. Of course the number of object waves increased for this last group. The objects used in the experiments are described bellow: Object No. 1 is a diffuse object measuring 2 cm x 2 cm and formed by a matrix of 5 x 5 specific sources equidistantly distributed with an opaque square in the center measuring 1 cm x 1 cm. It generated N = 16 object waves (Figure 3a). Object No. 2 is a diffuse object measuring 2 cm x 2 cm and formed by a matrix of 8 x 8 specific sources equidistantly distributed with an opaque square in the centermeasuring 1 cm x 1 cm. It generated N = 48 object waves (Figure 3b). Object No. 3 is a diffuse object measuring 2 cm x 2 cm and formed by a matrix of 5 x 5 specific sources equidistantly distributed. It generated N = 25 object waves (Figure 3c). Object No. 4 is a diffuse object measuring 2 cm x 2 cm and formed by a matrix of 8 x 8 specific sources equidistantly distributed. It generated N = 64 object waves (Figure 3d). Object No. 5 is a diffuse object measuring 4.5 cm x 4.5 cm and formed by a matrix of 18 x 18 specific sources equidistantly distributed. It generated N = 324 object waves (Figure 3e).

The circular spatial filter of the sheet corresponding to the matrix of 5 x 5 sources had a diameter of (1.45 ± 0.02) mm, and therefore its area was (1.65 ± 0.04) mm^2. The filter corresponding to the matrix with 8 x 8 and 18 x 18 sources had a diameter of (0.97 ± 0.02) mm and an area of (0.73 ± 0.03) mm^2.

Intermodulation noise greatly influences diffuse object holograms and is also a noise that depends on the object's spatial frequency. Thus, by introducing a larger size, we increase this spatial frequency range and it then becomes necessary to see if this modification really influences the hologram's SNR. The information corresponding to the spatial frequencies, ν, that define the matrix object is shown in Table I. The maximum spatial frequency, ν_{max}, the minimum spatial frequency, ν_{min}, and the total number of spatial frequencies that each range provides are shown for each object. The error in determining these spatial frequencies throgh geometric measurements is 5%.

Table I

Object	ν_{max} (lines/mm)	ν_{min} (lines/mm)	number of spatial frequencies	ν (lines/mm)
No. 1	95	95	1	95
No. 2	92	66	2	66, 92
No. 3	95	24	3	24, 47, 95
No. 4	92	13	4	13, 39, 66, 92
No. 5	223	13	8	13, 39, 66, 92, 118, 144, 170, 223

In the study of holograms recorded from the matric objects described above, the parameters that have been most closely analyzed were diffraction efficiency and SNR, because we consider these the most important in relation to the characteristics of these holograms. The definition of diffraction efficiency is given by the relation between the intensity of the set of first order diffracted waves and the intensity of the incident light of the reconstruction beam. However, regarding SNR, there are some details particular to each object that must be taken into account:

Object No. 1:

$$\mathrm{SNR} = \frac{\frac{1}{2}\sum_{i=1}^{2} I_{max\,i}}{I_{min}}$$

Object No. 2:

$$\mathrm{SNR} = \frac{\frac{1}{4}\sum_{i=1}^{4} I_{max\,i}}{I_{min}}$$

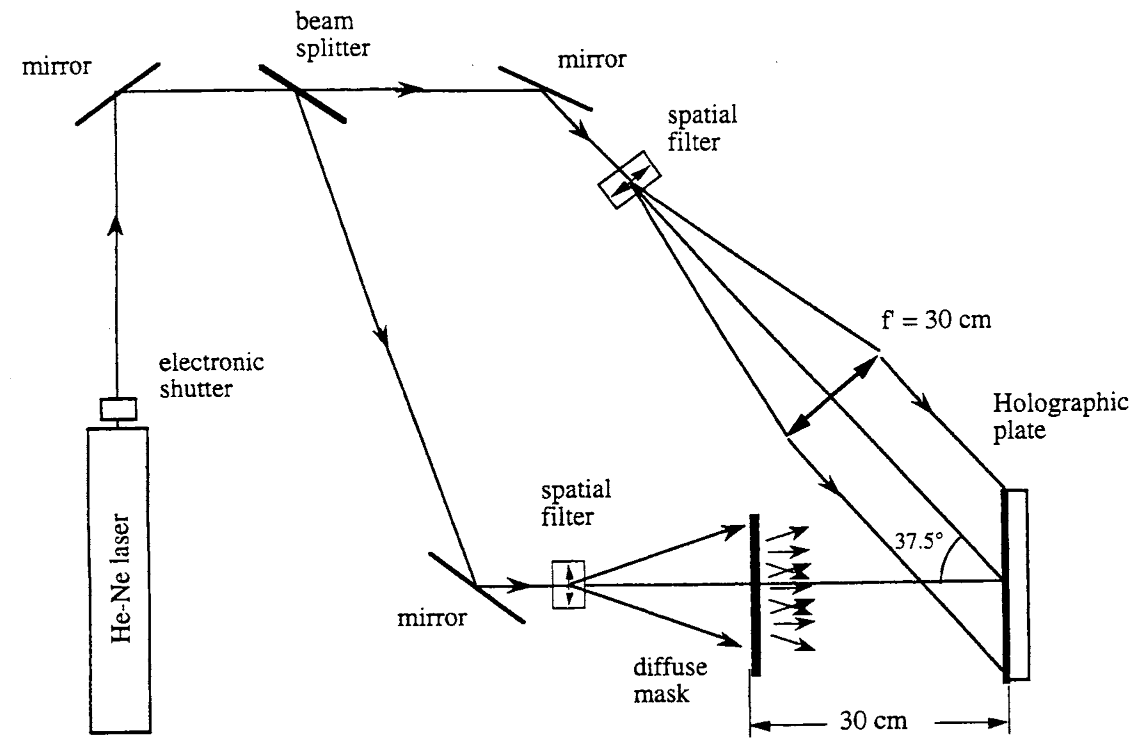


Figure 1

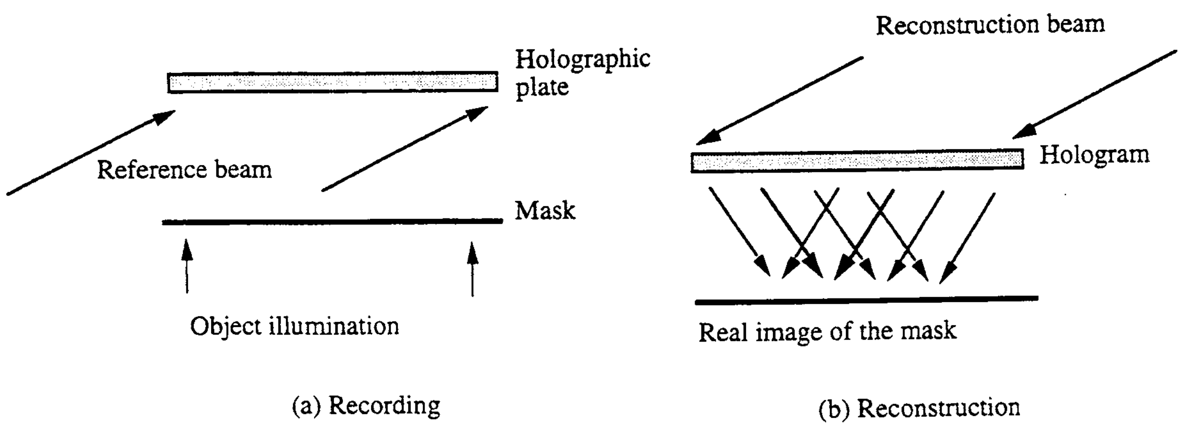
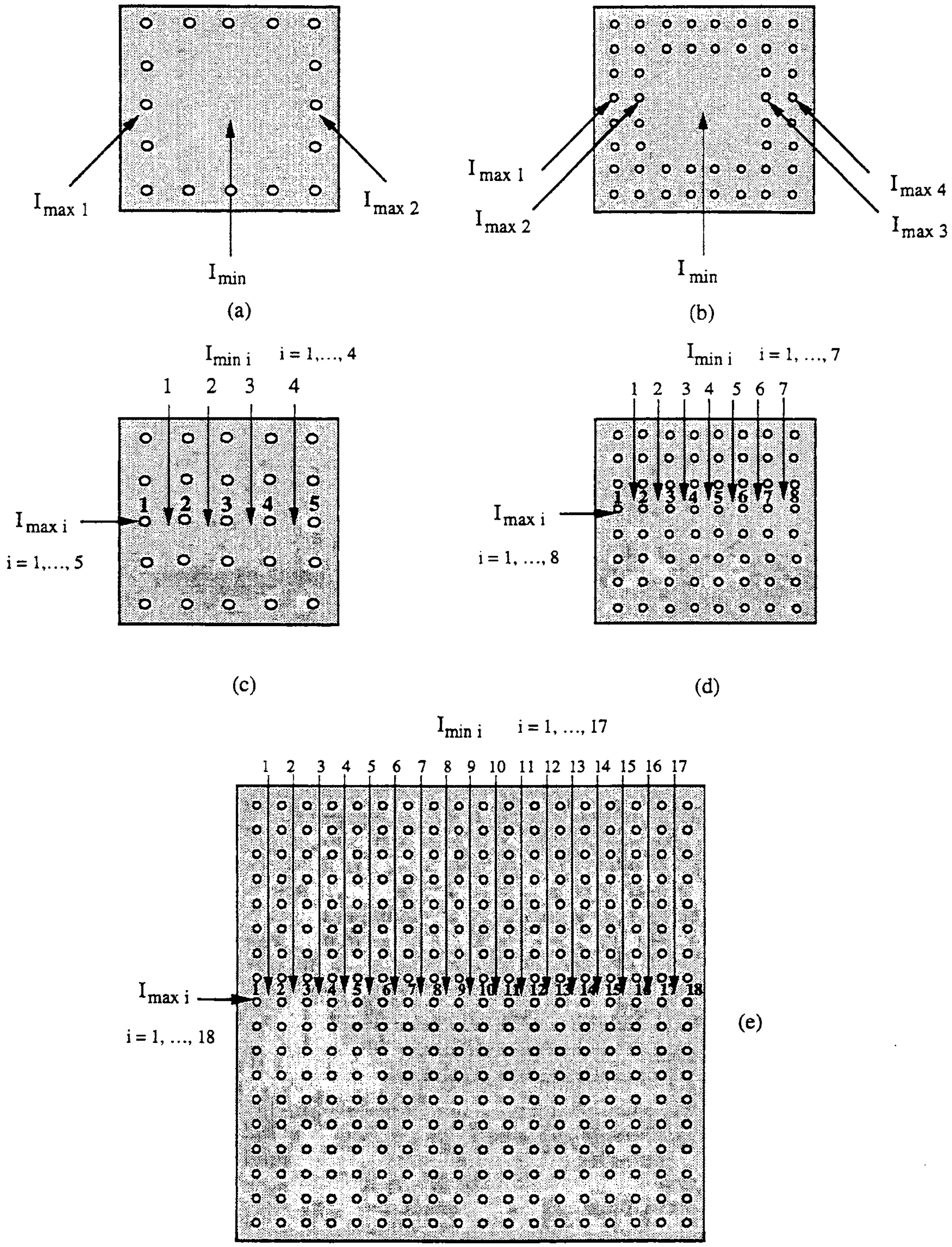


Figure 2



I max 1
I max 2
I min
(a)
I max 1
I max 2
I max 3
I max 4
I min
(b)
I min i i = 1,..., 4
I max i
i = 1,..., 5
(c)
I min i i = 1, ..., 7
I max i
i = 1, ..., 8
(d)
I min i i = 1, ..., 17
I max i
i = 1, ..., 18
(e)

Figure 3

Object No. 3:

$$SNR = \frac{\frac{1}{5}\sum_{i=1}^{5} I_{max\ i}}{\frac{1}{4}\sum_{i=1}^{4} I_{min\ i}}$$

$$SNR_{overall} = \frac{\frac{1}{2}\{\ maximum\ [I_{max\ 1,2}] + maximum\ [I_{max\ 4,5}]\ \}}{minimum\ [I_{min\ 2,3}]}$$

Object No. 4:

$$SNR = \frac{\frac{1}{8}\sum_{i=1}^{8} I_{max\ i}}{\frac{1}{7}\sum_{i=1}^{7} I_{min\ i}}$$

$$SNR_{overall} = \frac{\frac{1}{2}\{\ maximum\ [I_{max\ 1,2}] + maximum\ [I_{max\ 7,8}]\ \}}{minimum\ [I_{min\ 2,3,4,5,6}]}$$

Object No. 5:

$$SNR = \frac{\frac{1}{18}\sum_{i=1}^{18} I_{maxi}}{\frac{1}{17}\sum_{i=1}^{17} I_{mini}}$$

$$SNR_{overall} = \frac{\frac{1}{2}\{\ maximum\ [I_{max\ 6,7}] + maximum\ [I_{max\ 12,13}]\ \}}{minimum\ [I_{min\ 7,8,9,10,11}]}$$

The intensities I_{max}, I_{min} and I_i that appear in the definitions of the SNR and the overall SNR are defined in Figure 3.

In the matrix objects that do not have an opaque square in the middle (numbers 3, 4 and 5), two SNRs were identified. The first is typical of these objects[5], and the second, called overall SNR, was introduced in order to compare its values with values obtained when using previous experiments with diffuse obejects. In this way we were able to make sure that both the range of spatial frequencies associated with the signal and the range of spatial frequencies associated with the noise always remained constant. This makes it possible to compare the data obtained with those presented in previous papers. The intensities I_{max}, I_{min}, and I_i of the diffracted beam were measured using a photodetector with a range up to 10^{-7} W/cm^2 to scan the real reconstructed image. The diffraction efficiency was measured in the reconstructed image with the same photodetector and as a ratio between the diffracted and the incident beam. According to the experimental results and the repeatability of the photochemical process, the error in diffraction efficiency was 5% an in SNR, 7%.

Several holograms were made using Agfa-Gevaert 8E75 HD, a fine grain, silver halide emulsion with a glass plate as the substrate. The holograms were recorded at 633 nm using a He-Ne laser with a K = 5 reference-to-object beam-power-ratio for each exposure. The reference beam was collimated and it was polarized perpendicular to the plane of incidence. The distance of the object from the recording medium was 30 cm and the reference beam formed a 37.5° angle with the normal of the holographic plate which was parallel to the object (Figure 1). The N object waves were make to interfer with an expanded plane wave reference beam as can be seen in Figure 2 (a).

After exposure, the plates were developed in PAAAC developer (for composition, see Table III). This developer was created in our Laboratory[6]. The developed plates were rinsed briefly and bleached without a fixation step. The bleach bath used in these experiments was EDTA (for composition, see Table III), a rehalogenating bleach bath. Details of the processing schedule as well as the developer and bleach bath formulas are given in Tables II and III.

Table II

Step Procedure	Time (min)
1. Develop	3
2. Rinse in running water	1
3. Bleach	≈ 3
4. Wash in running water	5

All solutions at 20 C

Table III

PAAAC developer	
Sodium carbonate	120 g
Ascorbic acid	18 g
Phenidon	0.5 g
Distilled water	1 litre
EDTA Rehalogenating bleach bath	
Ferric sulfate	30 g
Potassium bromide	30 g
Shulphuric acid	10 ml
Distilled water to make	1 litre

The holograms were read-out in air with the conjugate of the collimated reference wave, and the diffracted output beam formed the real image of the object considered (Figure 2 (b)). The diffraction efficiency and the SNR were measured using the same wavelength that was used during the recording stage. In Figure 4, we have shown diffraction efficiency as a function of exposure for objects with matrix distribution and an opaque zone in the middle. Likewise, if we look at Figure 5 we can see that for diffuse objects with a complete matrix distribution, the same thing happens. In Figure 6 the SNR is shown as a function of exposure for diffuse objects with matrix distribution and an opaque zone in the middle. Figures 7 and 8 show the SNR and the overall SNR as a function of exposure in order to emphasize that there is a difference between SNR and overall SNR. Figure 9 shows the overall SNR as a function of exposure for the diffuse objects that have complete matrix distribution. In the three previous figures we see that the SNR decreases when the number of waves increases regardless of exposure. Therefore the number of waves yields the SNR and the overall SNR. The general conclusion that can be drawn from these experimental results is that when the number of object waves increases, both the diffraction efficiency and the SNR approach the value corresponding to the primary diffuse object, which therefore can be considered as the limit.

Figure 10 compares the SNR of object No. 4 (64 waves) with the SNR of object No. 5 (324 waves). We can see that there is a range of exposures, specifically between 10 and 50 $\mu J/cm^2$ (linear region of the D-log E curve of the developer), in which both have similar values, but for the rest of the exposures, the SNR corresponding to 64 waves had better values than the one corresponding to 324 waves. This is fundamentally due to the fact that the larger-sized object, which is the one that produces 324 waves, also produces a larger number of spatial frequencies in the noise space, which increases the intermodulation noise and therefore decreases the SNR. By representing the overall SNR of objects No. 4 and 5 graphically, as we can see Figure 11, we find that even though the same angular range for these two parameters has been maintained -and therefore the same range of spatial frequencies- the total number of waves that come from the object -and therefore the real range of spatial frequencies that the object contributes- affects the measurements.

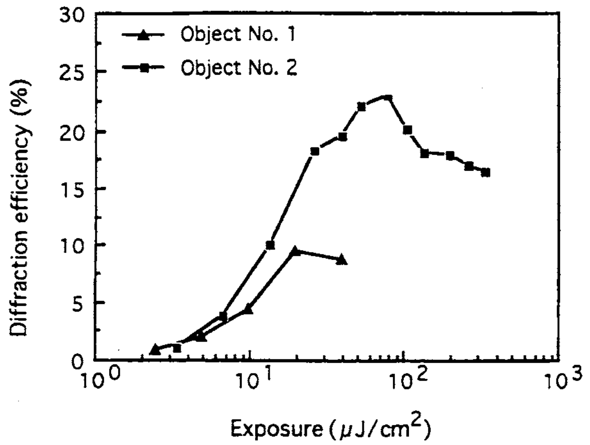


Figure 4

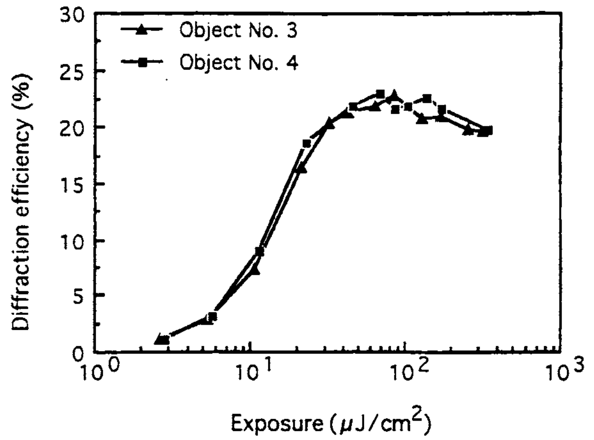


Figure 5

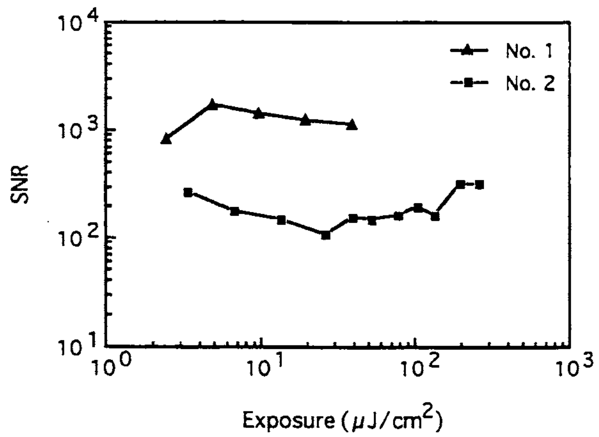


Figure 6

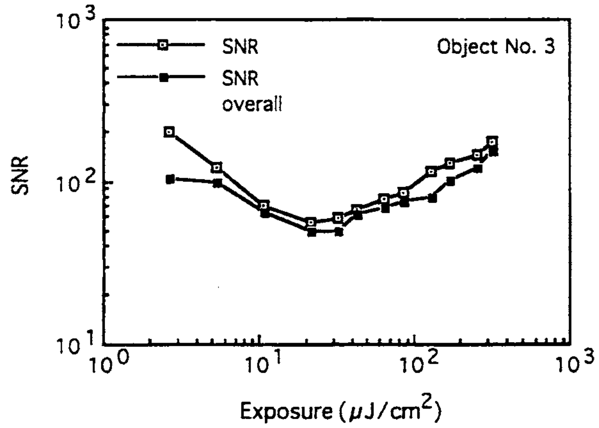


Figure 7

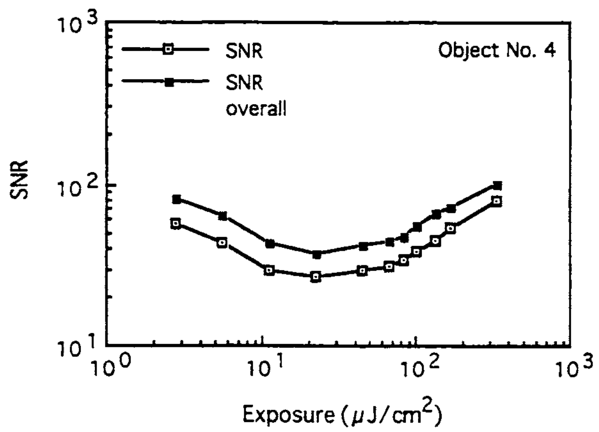


Figure 8

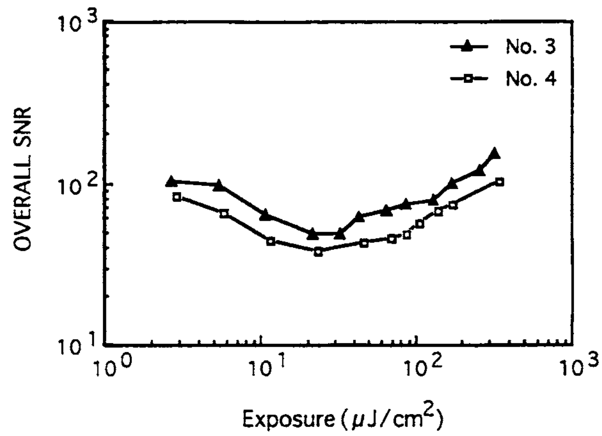


Figure 9

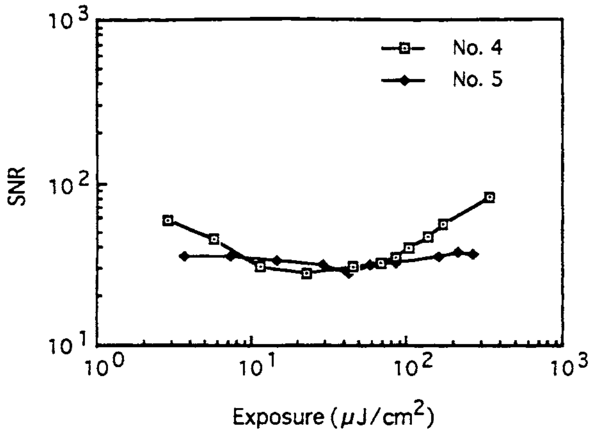


Figure 10

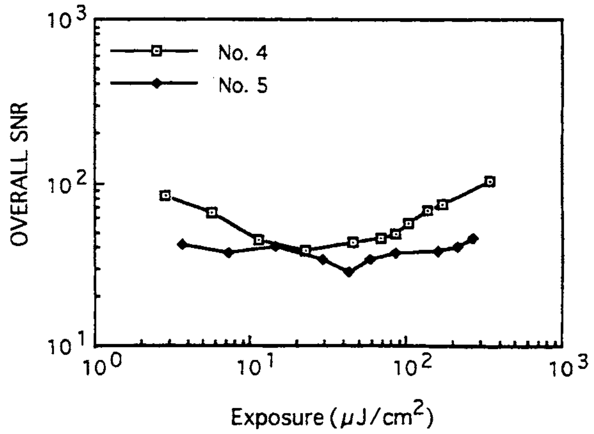


Figure 11

3 . CONCLUSIONS

In summary, a study was done on multiplexed volume phase holograms made in bleached photographic emulsion with applications in optical storage. The experimental measurements presented in this paper on the SNR of diffuse-object holograms shows that there does exist a correlation between noise and the number of waves that are stored coherently. These results show that there is a connection between the value that is hoped for as a minumum when N waves are stored and the noise that appears when they are reconstructed at the same time. The influence of the spatial distribution on the SNR is weak, and depends mainly on the number of waves. A clear relation between the spatial distribution of the object wave and the final SNR exists. Prior to this, there has been no theoretical model that justifies the experimental results shown in this paper. However, it is possible that by using the Kogelnik model[7] applied to a large number of object waves, the relation between SNR and the number of waves can be established, as has been suggested by Kostuk[8] in the past even though his theoretical work was limited to considering 10 object waves. However, our measurements show that the worst SNR can be easily determined by studying the hologram of a diffuse object. Further investigations and an understanding of the processes generating the noise are required for optimization of these recording materials and for their successful application in interconnection systems[9] and holographic optical memories[10,11].

4 . ACKNOWLEDGMENTS

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