Diffraction efficiency and signal-to-noise ratio of multiplexed volume phase holograms recorded in a photographic emulsion

R. Fuentes[1], A. Beléndez[2] and A. Fimia[1]

(1) Laboratorio de Optica. Departamento Interuniversitario de Optica
Universidad de Alicante. Apdo. No. 99. E-03080 Alicante, Spain

(2) Departamento de Ingeniería de Sistemas y Comunicaciones
Universidad de Alicante. Apdo. No. 99. E-03080 Alicante, Spain

Phone: + 34 - 6 - 590 35 09
Fax: + 34 - 6 - 590 34 64
e-mail: fimia@vm.cpd.ua.es

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ABSTRACT

The problems related to noise that come up during the recording and the reconstruction of holograms used in optical data storage or in massive optical interconnection systems are quite similar and can be analyzed in order to improve the quality of the images that these optical systems provide. In this paper we will analyze noise in cases in which several coherent object waves are simultaneously stored in a phase recording material in a way that allows us to obtain information about the relationship that exists between the recording material and the number of waves that are being stored. The material used in this study is Agfa Gevaert 8E75 HD holographic film processed with a rehalogenating type bleach bath without a fixation step. Additionally, we show experimentally that it is possible to holographically store more than 400 waves at the same time (in a coherent fashion) using the same storage geometry, with a signal to noise ratio greater than 20 and an average diffraction efficiency of 15%.

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1. INTRODUCTION

In several important applications of holography such as interconnection systems or holographic optical memories it is necessary to multiplex several functions or many optical components in the same thin film recording material [1]. 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 [2], because a spectrum of spatial frequencies occurs there. On the other hand, the theoretical maximum storage density (bit per unit of hologram area) of an ideal (noise-free) thick hologram is proportional to the hologram thickness [3]. However, in actual holograms, noise is present and this 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 optical interconnects [4] or information storage [5, 6].

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 [7]. 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 [8, 9].

The aim of the present paper is to present experimental results on the influence of the number of object waves and their spatial distribution on diffraction efficiency and

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SNR for bleached holograms 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. CHARACTERISTICS OF THE OBJECTS BEING ANALYZED

2.1.-Description of the objects

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 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 and had a total area of 2 x 2 cm^2. Some of the objects had an opaque zone in the center which mirrored the primary diffuse object, 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: A diffuse object measuring 2 x 2 cm^2 with an opaque central zone measuring 1 x 1 cm (Figure 3a).

Object No. 2: This object was formed by a matrix of 5 x 5 specific sources with an opaque square in the center. It generated 16 object waves (Figure 3b).

Object No. 3: This object was formed by a matrix of 8 x 8 specific sources with an opaque square in the center. It generated 48 object waves (Figure 3c).

Object No. 4: This object was formed by a matrix of 5 x 5 specific sources. It

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generated 48 object waves (Figure 3d).

Object No. 5: This object was formed by a matrix of 8 x 8 specific sources. It generated 64 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 sources had a diameter of (0.97 ± 0.02) mm and an area of (0.73 ± 0.03) mm^2. To make it possible to compare the results obtained with matricial objects and object No. 1, we assumed that one wave was emitted from each hole in object No. 5. Then we calculated approximately how many of these hole areas there were. As the illuminated area of the diffuse object was 300 mm^2, we estimate that 411 waves are emitted from object No. 1. Object No. 1 is the closest to the limit of generation of an infinite number of waves.

2.2.-Parameters studied

In the study of holograms recorded from the matrix objects described above, the parameters that were most carefully 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:

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

Object No. 2:

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

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Object No. 3:

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

Object No. 4:

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

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

Object No. 5:

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

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

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 4 and 5), two SNRs were identified. The first is typical of these objects [10], and the second, called overall SNR, was introduced in order to compare its values with values obtained when using object No. 1. In the definition of overall SNR, we took into account the maximum values of the matrix distribution that emerge within the shiny

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angular range that object No. 1 forms from the center of the holographic plate. We did the same for the minimums, this time keeping in mind the angle that is formed due to the opaque square. 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.

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%.

2.3.-Spatial frequencies produced by objects with matrix distribution

Intermodulation noise may depend on the spatial frequency of the pattern generated by the object and the reference wave. In this sense, objects with matrix distribution differed from object No. 1: The ranges of spatial frequencies that are covered are different and for diffuse objects this range is continuous while for the other objects it is discrete. The information about the spatial frequencies, ν, of the different objects 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 calculated for each object. In this table we also include the data corresponding to the primary diffuse object in order to compare all of the cases. The error in determining these spatial frequencies is around 5%.

3. RECORDING OF THE MULTIPLEXED HOLOGRAMS

Several holograms were made using Agfa-Gevaert 8E75 HD, a fine grain,

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silver halide emulsion with a glass plate as the substrate. The holograms were recorded at 632.8 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 shows a schematic representation of the geometry used in our experiments. The N object waves were make to interfer with an expanded plane wave reference beam as can be seen in Figure 2 (a).

Reflections from the glass plate were eliminated by placing an index-matched absorbing layer against the glass side of the photographic plate which preventted the recording of unwanted gratings. After exposure, the plates were developed in PAAAC developer (for composition, see Table III). This developer was created in our Laboratory [11]. 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. In this rehalogenating bleach, the bleach baths contain a rehalogenating agent (potassium bromide) which converts most of the developed silver back into a silver halide. In this case a phase hologram is obtained mainly due to the transfer of silver halide from the unexposed to the exposed areas. Rehalogenating bleaches have the advantage that the resulting emulsion thickness change produced by these baths is very small ($< 0.05\ \mu m$) in the nominally thick $6\ \mu m$ film [12], since the overall removal of silver salts from the emulsion is minimal. Also it is assumed that the average refractive index does not change appreciably as a result of processing [12]. As thickness and the average refractive index of the holographic recording material show very little change when these types of chemical processings are used, the reconstruction geometry of the holograms corresponding to maximum diffraction efficiency coincide with the construction geometry if recording and readout wavelengths are equal. This implies that Bragg's Law is complied with in the reconstruction stage, even though sometimes there is a displacement of the Bragg angle which is caused by shear-type effects [13]. Details of the processing schedule as well as the developer and bleach bath

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formulas are given in Tables II and III.

4. EXPERIMENTAL RESULTS AND DISCUSSION

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 order to analyze the experimental results we obtained, we have separated those that correspond to diffuse objects with an opaque zone in the middle from those that correspond to a diffuse object with a complete matrix distribution. In Figure 4 (a), we have shown diffraction efficiency as a function of exposure for objects with matrix distribution and an opaque zone in the middle. We see that as the number of object waves increases, the diffraction efficiency tends to approach the diffraction efficiency of object No. 1. Likewise, if we look at Figure 4 (b) we can see that for diffuse objects with a complete matrix distribution, the same thing happens. In Figure 5 the SNR is shown as a function of exposure for diffuse objects with matrix distribution and an opaque zone in the middle, and we see that as the number of object waves increases, the SNR function decreases and approaches that of the primary diffuse object.

Figure 6 shows 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 7 shows the global SNR as a function of exposure for the diffuse objects that have complete matrix distribution. We see that when the number of object waves increases, the overall SNR function decreases and approaches that of object No. 1. In the two 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. Figure 8 (a) shows the SNR as a function of the number of waves and of the selection of any exposure value which would be acceptable as a means of observing its

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general behavior. Therefore in Figure 8 (a), the SNR appears as a function of the number of waves for diffuse objects with an opaque zone in the middle. The SNR value corresponding to the exposure that produced the maximum diffraction efficiency in each case was used as the SNR for each object studied. Figure 8 (b) also shows these values but for a different type of diffuse object. 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.

5. CONCLUDING REMARKS

A study was done on multiplexed volume phase holograms made in bleached photographic emulsion. The experimental results presented in this paper on the SNR of phase holograms in which a finite number of object waves were stored, show that there exists a correlation between noise and the number of simultaneously stored coherent waves. It has been shown that both the number and the geometric distribution of objects waves influence the SNR. The smallest SNR is obtained with diffuse object containing a continuous spectrum of spatial frequencies. 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 [14] 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 [1] 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

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materials and for their successful application in interconnection systems [4] and holographic optical memories [5, 6].

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FIGURE CAPTIONS

Figure 1.- Experimental set up for recording spatial frequency multiplexed volume phase diffuse-object holograms of N object waves. M: mirror, SF: spatial filter, BS: beam splitter, ES: electronic shutter, f': focal lenght of the collimating lens.

Figure 2.- (a) Recording and (b) reconstruction of diffuse object holograms.

Figure 3.- (a) Object No. 1, (b) object No. 2, (c) object No. 3, (d) object No. 4 and (e) object No. 5.

Figure 4.- Diffraction efficiency as a function of exposure for (a) objects No. 1 (DO), No. 2 (16 waves) and No. 3 (48 waves), and (b) objects No. 1 (DO), No. 4 (25 waves) and No. 5 (64 waves). Reconstruction is done in the Bragg angle.

Figure 5.- SNR as a function of exposure when reconstruction is done in the Bragg angle and when objects No. 1 (DO), No. 2 (16 waves) and No. 3 (48 waves) are used.

Figure 6.- SNR and overall SNR as a function of exposure when reconstruction is done in the Bragg angle. (a) Object No. 4 (25 waves). (b) Object No. 5 (64 waves).

Figure 7.- Overall SNR as a function of exposure when reconstruction is done in the Bragg angle and objects No. 1 (DO), No. 4 (25 waves), No. 5 (64 waves) are used.

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Figure 8.- (a) SNR as a function of the number of waves for object No. 2 (16 waves), No. 3 (48 waves) and No. 1 (411 waves). (b) Overall SNR as a function of the number of waves for object No. 4 (25 waves), No. 5 (64 waves) and object No. 1 (411 waves).

TABLES

Table I.- Spatial frequencies for the diffuse objects used in the analysis.

Table II.- Processing schedule.

Table III.- Developer and bleach bath formulas.

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TABLE I

Object	ν_{max} (lines/mm)	ν_{min} (lines/mm)	number of frequencies	ν (lines/mm)
No. 1	105	53	continuous	from 53 to 105
No. 2	95	95	1	95
No. 3	92	66	2	66, 92
No. 4	95	24	3	24, 47, 95
No. 5	92	13	4	13, 39, 66, 92

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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

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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

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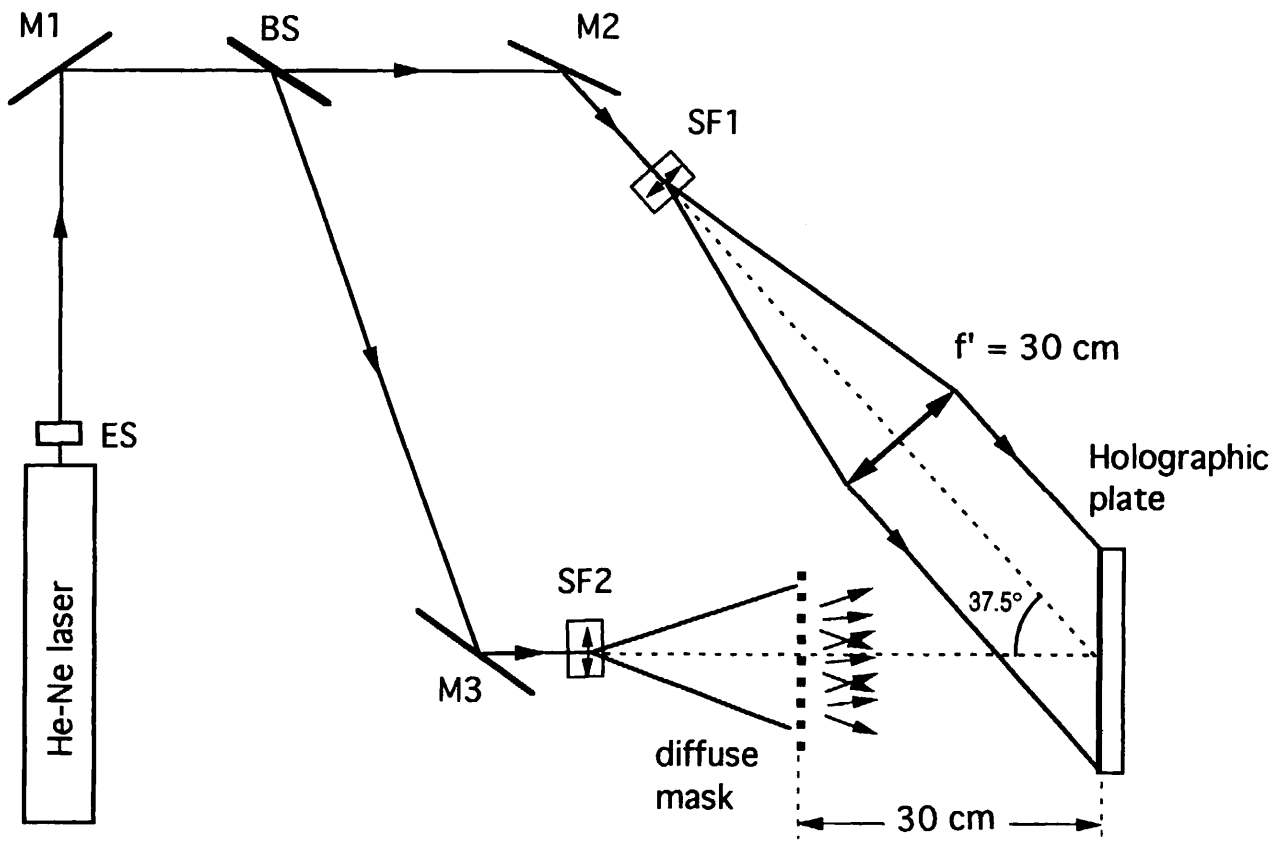

FIGURE 1
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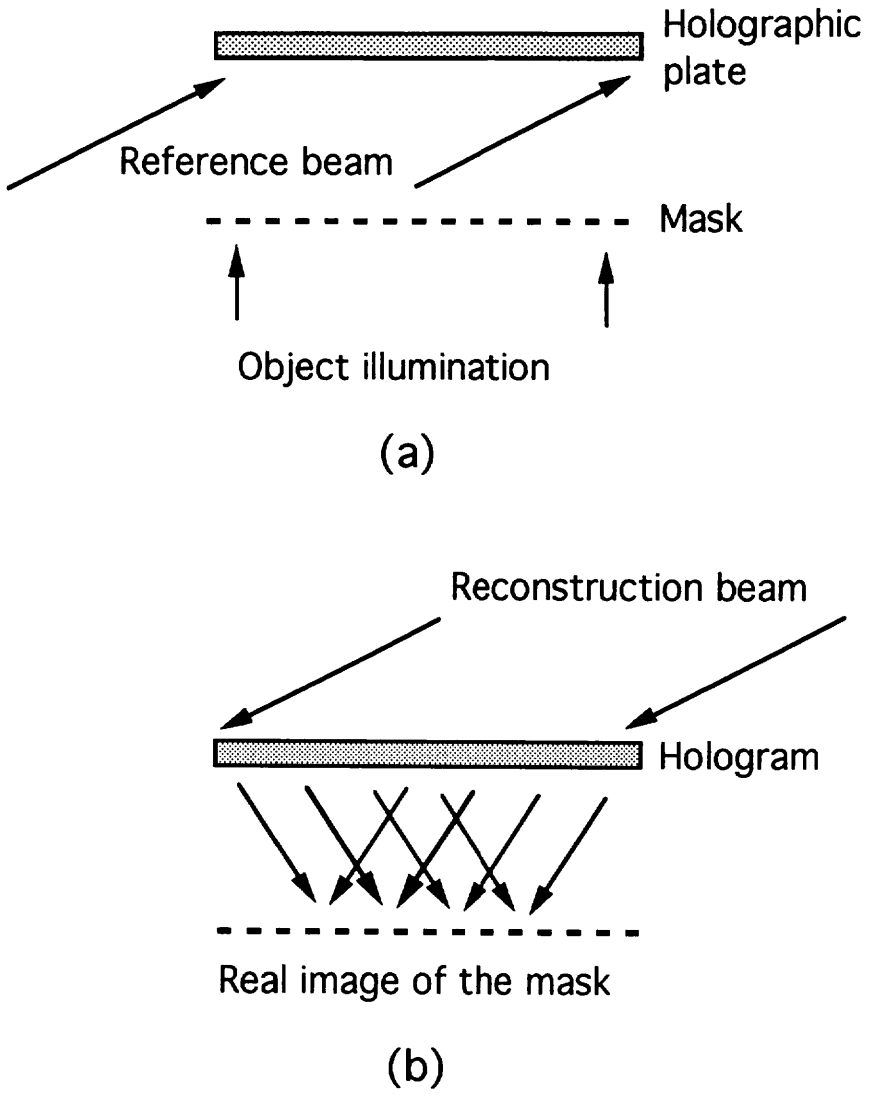

FIGURE 2
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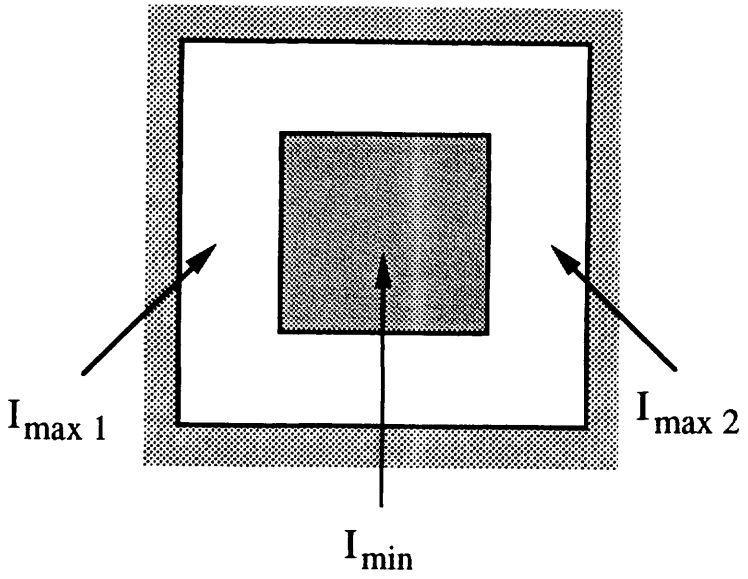

FIGURE 3 (a)
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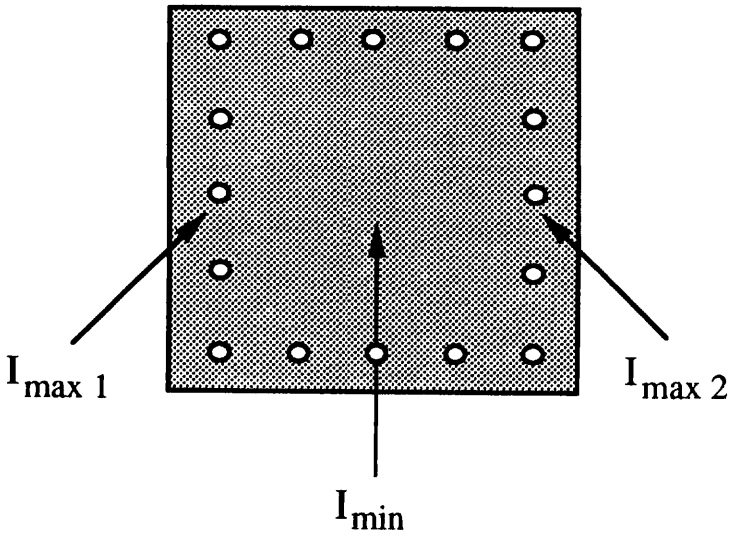

FIGURE 3(b)
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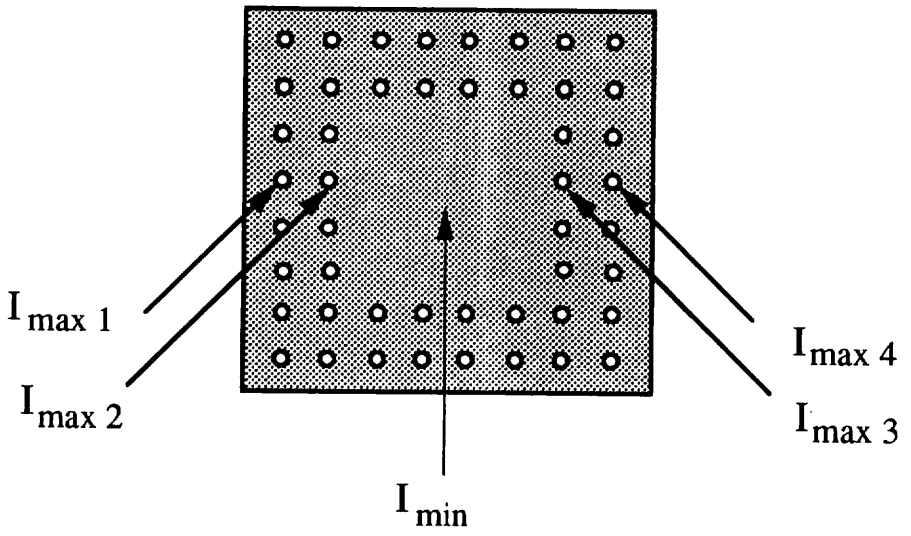

FIGURE 3(c)
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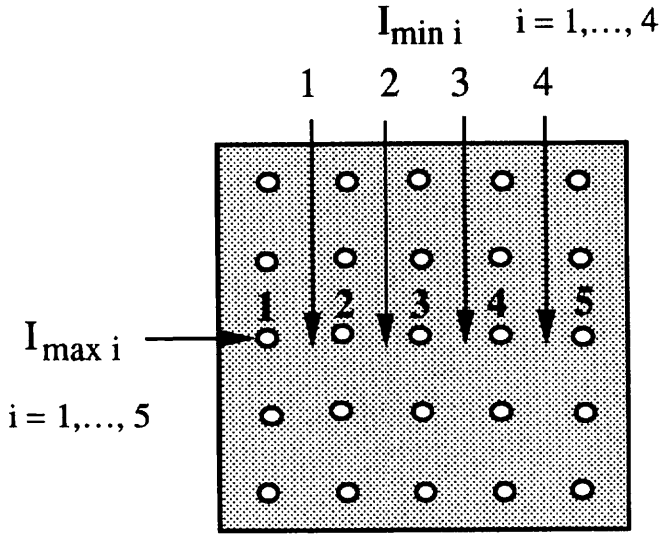

FIGURE 3(d)
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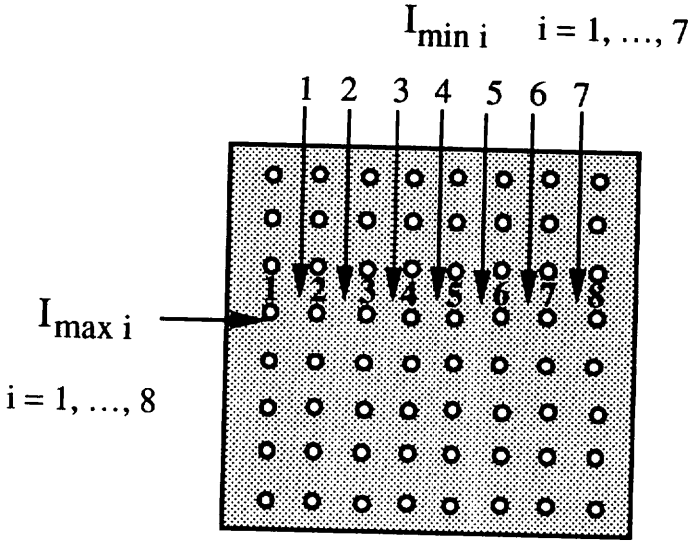

FIGURE 3(e)
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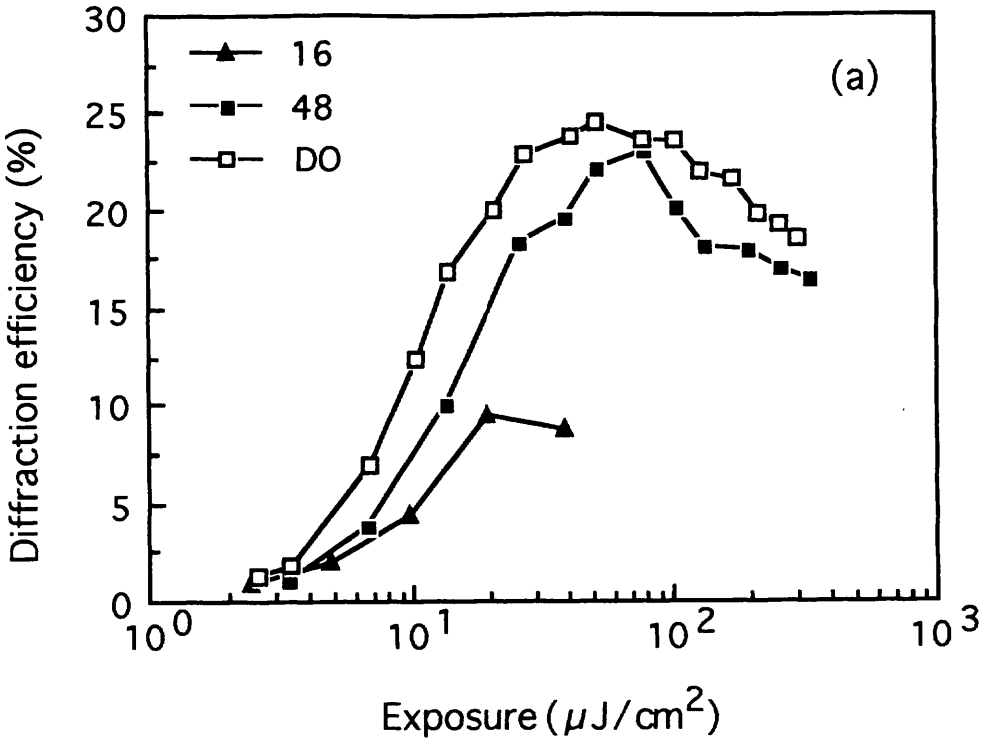
FUENTES, Rosa; BELÉNDEZ, Augusto; FIMIA, Antonio. "Diffraction efficiency and signal-to-noise ratio of multiplexed volume phase holograms recorded in a photographic emulsion". Applied Physics B: Lasers and Optics. Vol. 63, No. 1 (July 1996). ISSN 0946-2171, pp. 29-34 DOI: 10.1007/BF01112833



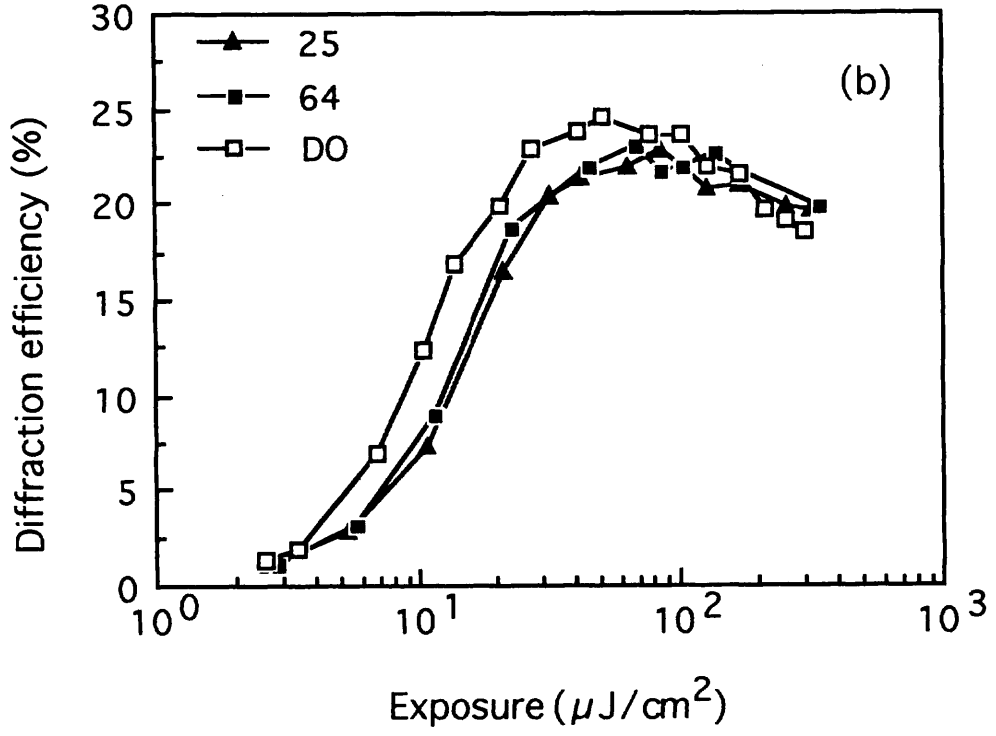


FIGURE 4
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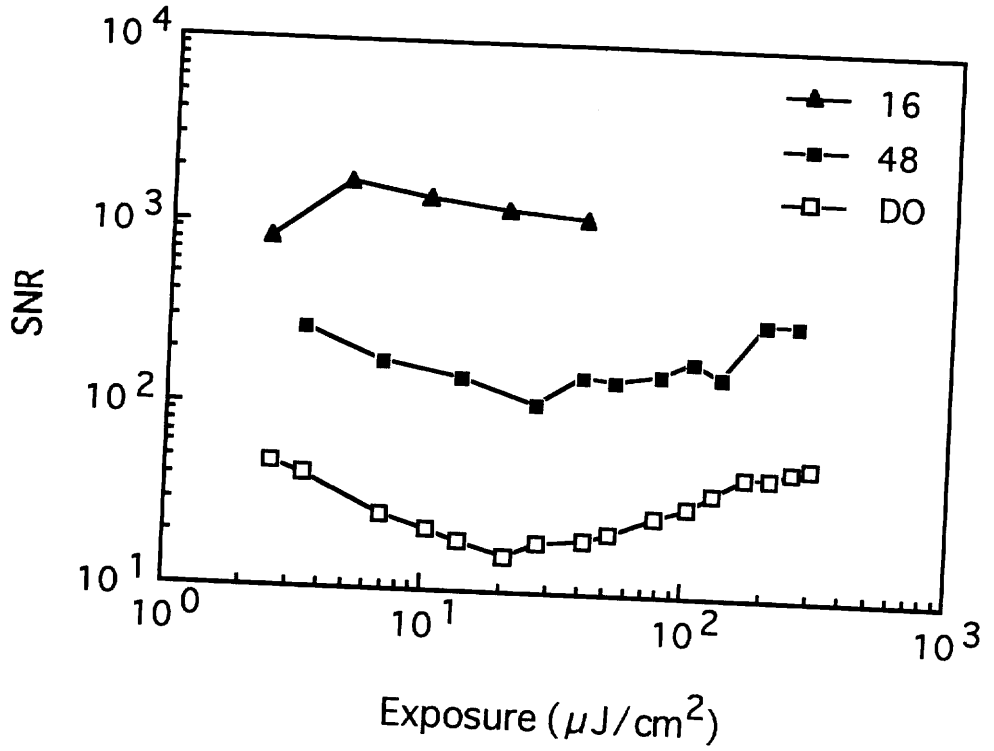

FIGURE 5
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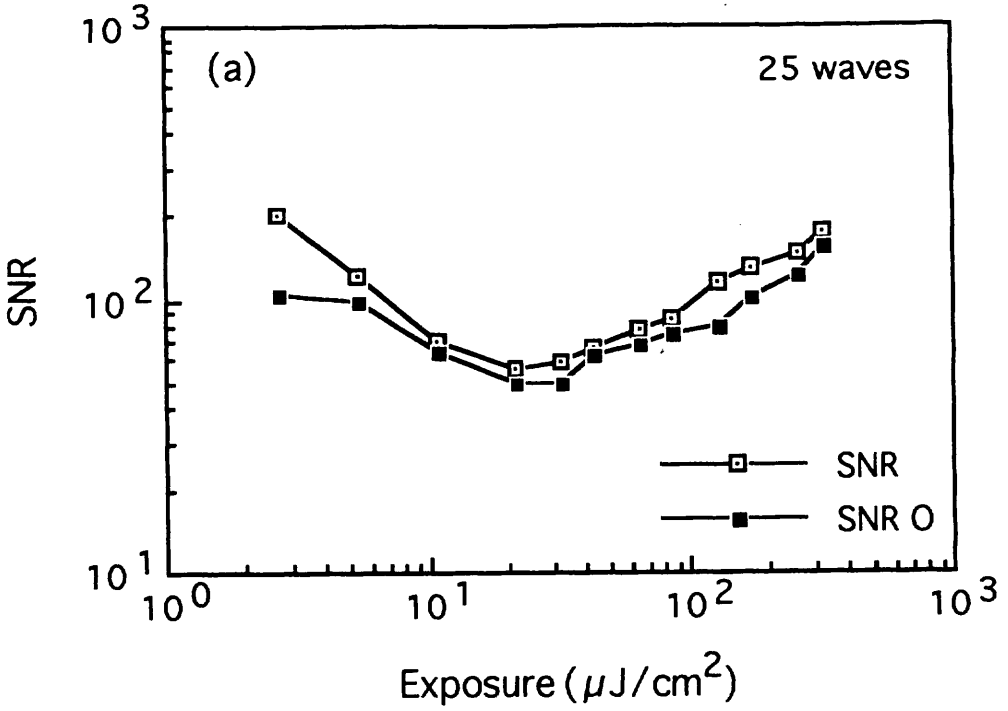

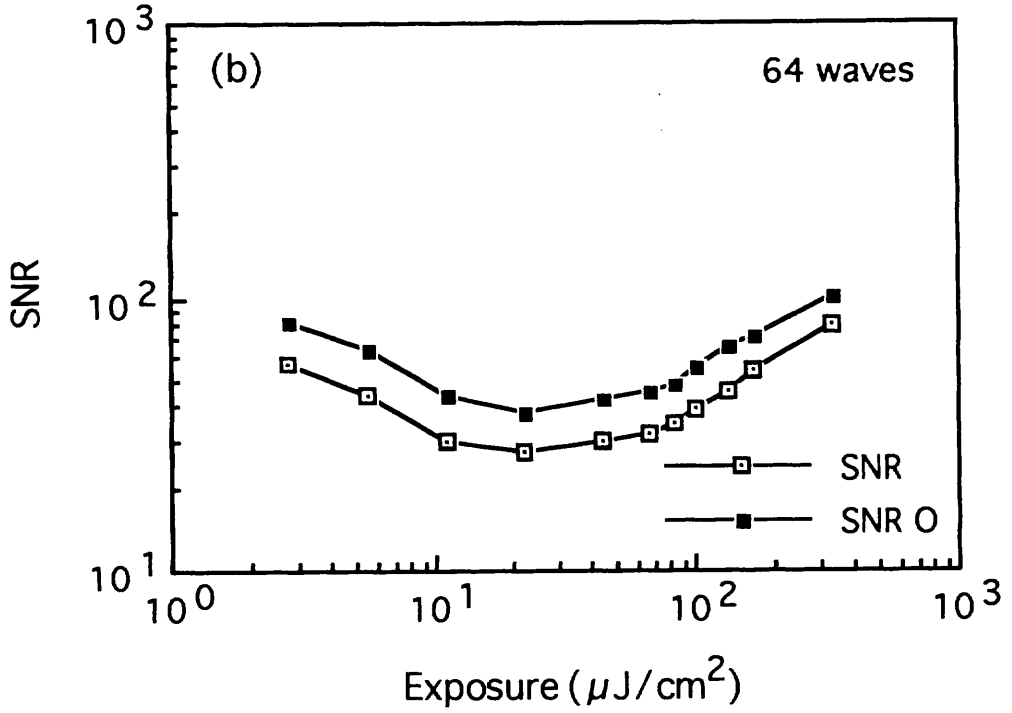

FIGURE 6
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FUENTES, Rosa; BELÉNDEZ, Augusto; FIMIA, Antonio. "Diffraction efficiency and signal-to-noise ratio of multiplexed volume phase holograms recorded in a photographic emulsion". Applied Physics B: Lasers and Optics. Vol. 63, No. 1 (July 1996). ISSN 0946-2171, pp. 29-34 DOI: 10.1007/BF01112833

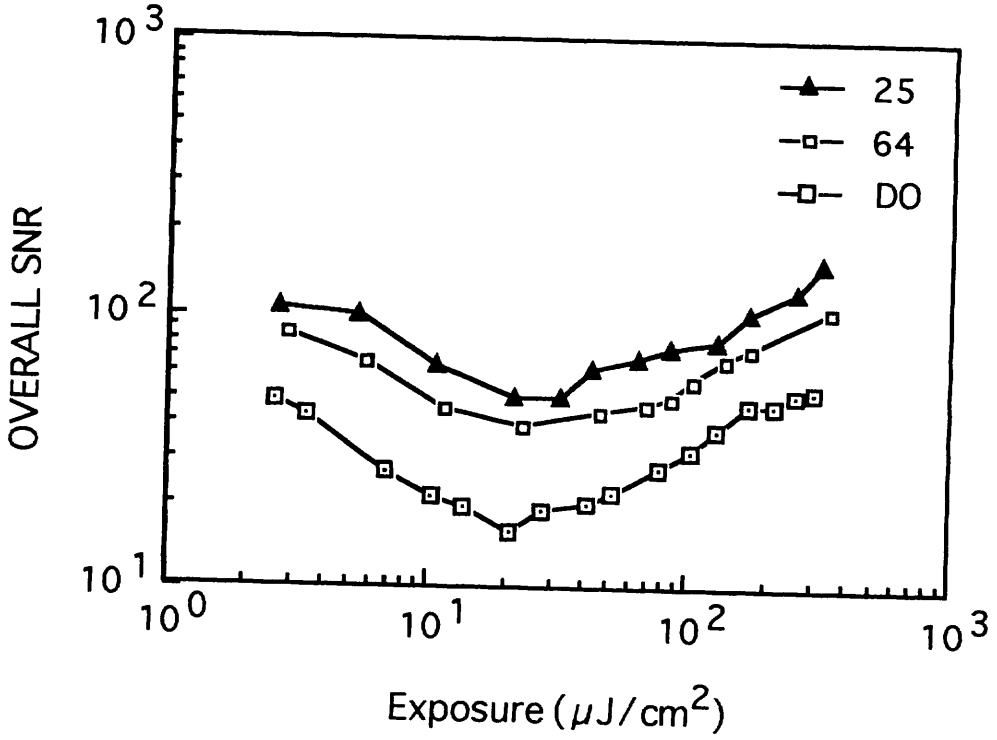

FIGURE 7
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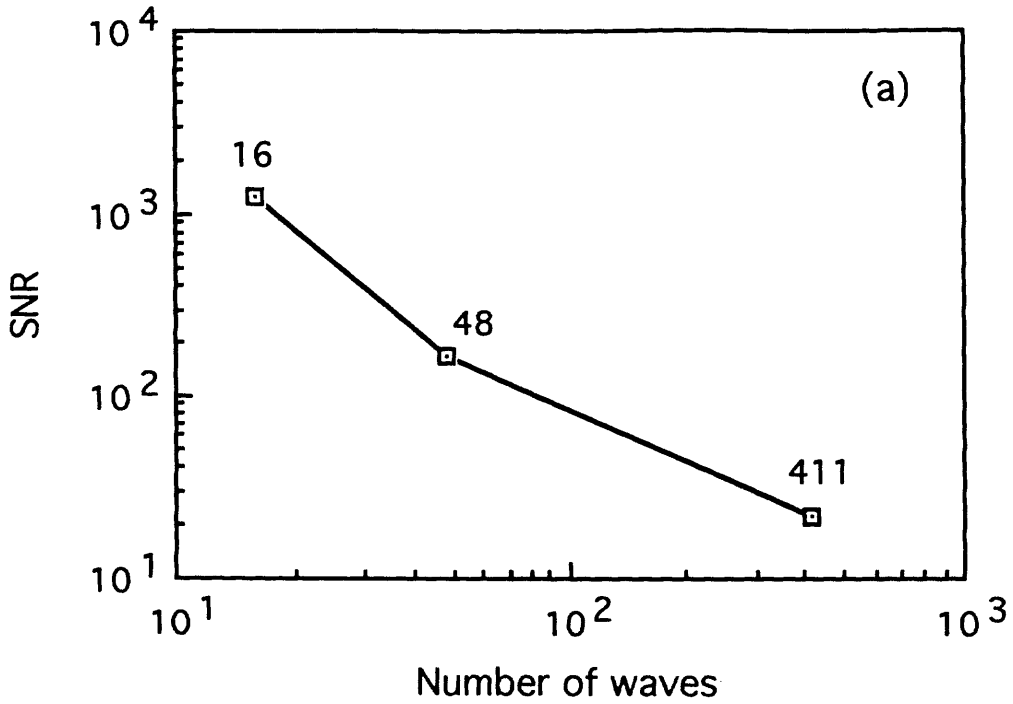
FUENTES, Rosa; BELÉNDEZ, Augusto; FIMIA, Antonio. "Diffraction efficiency and signal-to-noise ratio of multiplexed volume phase holograms recorded in a photographic emulsion". Applied Physics B: Lasers and Optics. Vol. 63, No. 1 (July 1996). ISSN 0946-2171, pp. 29-34 DOI: 10.1007/BF01112833



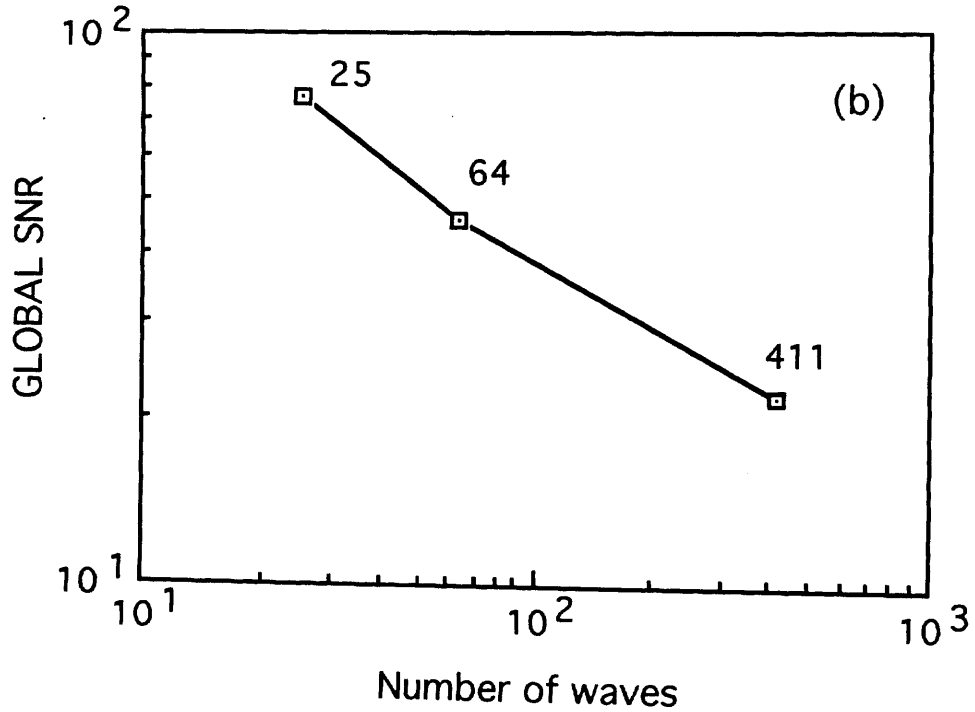


FIGURE 8

BELÉNDEZ, Augusto; FIMIA, Antonio. "Diffraction efficiency and signal-to-noise ratio of multiplexed volume phase holograms recorded in a photographic emulsion". Applied Physics B: Lasers Vol. 63, No. 1 (July 1996). ISSN 0946-2171, pp. 29-34 DOI: 10.1007/BF01112833