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Evaluation of Various Bleaching Processes for Single Exposure and Multiple Exposure Holograms

Gary S. Phipps, Murphy J. Landry, Clarence E. Robertson

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EVALUATION OF VARIOUS BLEACHING PROCESSES FOR
SINGLE EXPOSURE AND MULTIPLE EXPOSURE HOLOGRAMS

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ABSTRACT

Five bleaching techniques for Agfa Gevaert Scientia 10E75 high-resolution plates were evaluated as to their resultant diffraction efficiency and relative signal-to-noise ratio for identically recorded single exposure holograms. A cupric bromide bleach was judged to produce the "best" results. A series of tests was conducted using this cupric bromide to determine the optimum recording conditions for both single exposure and multiple exposure bleached holograms. Data are presented for diffraction efficiency, signal-to-noise ratio, and resolution of diffuse and focused image holograms for both single and multiple exposure cases using a nontrivial object. The diffraction efficiency of both types of hologram is improved by up to three orders of magnitude by bleaching. The signal-to-noise ratio of diffuse holograms is degraded by bleaching, but that of the focused image holograms is improved. The resolution of both types was not affected by bleaching. Bleached multiple exposure holograms were found to be similar to single exposures except that diffraction efficiencies were lower. It was found that the diffraction efficiency of a bleached hologram decreases with age.

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EVALUATION OF VARIOUS BLEACHING PROCESSES FOR SINGLE EXPOSURE AND MULTIPLE EXPOSURE HOLOGRAMS

I. Introduction

Agfa-Gevaert Scientia 10E75 glass plates are commonly used when holographic data are recorded because of their high resolution and low exposure requirements. A data recording system to measure high velocity surface motion is being constructed by Organization 5167. This system is designed to record multiple exposure holographic interferograms using a pulsed laser system. It was thought that bleached holograms might allow a greater exposure energy latitude to accommodate variations in the laser output power. An investigation of multiple exposure amplitude holograms using 10E75 plates was made earlier.¹ Additional data on similarly recorded, but bleached, 10E75 plates were needed to determine if bleaching was desirable. Five different bleaches were selected from the open literature for direct comparison. One of the five was selected as the "best", and fairly extensive tests were conducted with this one bleach formulation.

II. Previous Bleaching Investigations

As early as 1964 Cathey² reported bleaching a photographically recorded amplitude hologram using the bleach from Kodak's Chromium Intensifier process. Cathey's procedure was not the first reference to a phase type hologram,³ but it was the first published instance of producing one from conventional photographic materials.

A photographic phase hologram is recorded as path length variations through an emulsion due to thickness variations (surface relief), spatial refractive index variations, or, as is usually the case, a combination of both. Some work has been done to investigate the surface relief created by photographic development^{4,5} and subsequent bleaching methods.⁶ In general, the height of the surface relief is a maximum at a fairly low spatial frequency and is emulsion thickness dependent. Attempts have been made to develop tanning processes to enhance surface relief. In general, it is difficult to determine the contribution of the surface relief to the holographic reconstruction process. Because of this difficulty, most bleaching investigations concentrate on the spatial refractive index variations caused by various chemical salts in the emulsion while glossing over any contributions due to actual thickness variations.

Experiments conducted with various bleach formulations have resulted in published reconstruction diffraction efficiencies for a multitude of different cases. Detailed results reported with these bleaches have been as varied as the number of actual bleaches tried.

One difficulty in comprehending these data sources is that information about the experimental procedure is often incomplete. Even when sufficient information is given, it is difficult to directly compare results obtained with different processing and emulsion types. The more informative papers include detailed data on the dependence of diffraction efficiency on the prebleaching photographic optical density of the hologram. Nearly all experimenters agree that the optimum prebleach density for a bleached hologram is higher than for an amplitude hologram. Other details such as signal-to-noise ratio and optimum reference-to-object beam ratio (K) are sometimes not even discussed.

One of the major problems associated with high efficiency bleached holograms is the high background noise level which degrades the reconstructed image.^{7,8,9} Many methods of producing low noise, bleached holograms have been proposed. Young and Kittredge⁹ report that for 10E75, at least, the "intense diffuse glare" surrounding the reconstructed image is decreased with higher K values as well as with lower before-bleach densities. These conditions are the opposite of those required for a high efficiency bleached hologram but are similar to those of Graube,¹⁰ who noted that low scatter is achieved only with reduced diffraction efficiency.

Techniques have been considered to reduce the scattered noise of a particular hologram by altering or adding steps to the development/bleach procedure rather than by changing the recording parameters. Special drying procedures have been credited with decreasing the scattered noise of holograms recorded on Agfa 10E70¹¹ as well as Kodak 649F^{11,12} plates. Stress relief¹² and hardening of the emulsion before development^{12,13} are reported to produce lower noise. Chang and George¹⁴ have theorized that a reversal bleach process wherein the silver image of a developed but unfixed plate is dissolved, leaving only the original undeveloped silver halide crystals, should give superior noise suppression. The one thing that all these processes have in common is their relative processing complexity.

The other major problem with bleached holograms is their tendency to darken with exposure to light, thus reducing the diffraction efficiency. This printout effect, as it is called, is a problem since light must be used to read the information out of the hologram. At a very minimum, the readout beam used must not darken the hologram appreciably during the time necessary to extract information from it. Additional insensitivity to light would be desirable. The normal bleach process converts the developed image silver to a silver salt, usually a silver halide, silver chromate, or a silver ferricyanide. Unfortunately, these compounds are similar to the compounds used in the original photographic emulsion, and, as such, are themselves light sensitive. If enough light is absorbed by these compounds, they disassociate and again form metallic silver, darkening the bleached plate. The amount of light necessary to produce a given amount of darkening is inversely proportional to the absorption of the bleached silver salt as well as to its sensitivity to the particular

wavelength of light. As with the scattered noise, there are several procedures for dealing with the printout problem, each based on a different line of reasoning.

One procedure⁸ is to desensitize a halide bleached emulsion in a solution of the respective cupric or mercuric halogen CuO_2 , CuBr_2 , HgCl_2 , etc., adding enough extra halogen ions to the emulsion to hopefully discourage the disassociation process. McMahon and Maloney,¹⁵ however, attribute any effect of this process to decreased absorption of the plate rather than desensitization. It is suggested instead that a better way to produce a more stable bleached hologram is to form it by using a halide ion of a higher molecular weight. An end product of AgI is preferred to that of AgBr, with AgCl being a last resort. The desirability of AgI as an end product has been confirmed by Hariharan and Ramanathan.¹⁶

Hardening of the emulsion to discourage the light induced disassociation has also been tried.¹⁷ It is theorized that hardening produces a rigid matrix in which the mobility of the halide ions is greatly reduced. The procedure consists of a chemical hardening bath followed by a final heating step. Either step is said to give a lifetime improvement factor of 5, but together they produce an improvement factor of 55. A method in which desensitization is credited to removal of impurities from the emulsion is described by Lehmann, et. al. Norman¹⁸ used a modified form of this process as a starting point to produce his dye-induced stabilization technique. In this method, the emulsion is rendered less sensitive to a particular wavelength of light by the addition of an appropriate dye which is selected by experimentation.

Dichromated gelatin holograms do not exhibit the printout effect of normally bleached holograms, are very efficient, and give reconstructions comparable to that of Kodak G40F film.¹⁹ Their disadvantage is that they are 2 to 5 orders of magnitude less sensitive than normal holographic plates. Pennington, et. al.,²⁰ have devised a method of converting a photographically recorded hologram, by means of a halide bleach, into a hardened gelatin record with the stability advantages of the dichromated gelatin, while retaining the exposure sensitivity of the original plate. With no silver compounds in the emulsion, it is no longer light sensitive. The disadvantage is that it is a long and complicated process with many parameters affecting the final result. A second, simpler method²¹ for removing silver compounds from the bleached hologram involves bleaching in a solution that converts the silver to lead or nickel ferricyanide. The lead bleach produces holograms with slightly better diffraction efficiency and somewhat more resistance to printout than silver ferricyanide. They are apparently not as light insensitive as the hardened gelatin type.

III. Scope

For this study, five bleaches were used on Agfa 10E75 plates. The bleaches and the

reasons for their selection are listed below.

1. 10 gr/l Potassium ferricyanide⁸ chosen because of simplicity as well as supposed good diffraction efficiency and printout resistance.
2. 10 gr/l Mercuric chloride⁸ chosen for simplicity and supposed good diffraction efficiency.
3. 50 gr/l Cupric bromide plus associated chemicals reported by Lehmann,¹³ et. al., chosen for hardening and desensitizing, both of which should increase stability and signal-to-noise ratio.
4. Br Vapor. Dry bleach with reported superior resistance to printout.^{10,22}
5. Kodak Chromium Intensifier. This was being used at Sandia and was included for comparison purposes.

The five bleaches were judged by comparing the resultant diffraction efficiency and signal-to-noise ratio of identically recorded and bleached holograms.

IV. Experimental Results

10E75 Sensitometric Characteristics

To avoid possible processing variations due to manual agitation, all photographic plates were processed in a Kodak nitrogen burst agitation system. Rather extensive tests were undertaken to determine the sensitometric characteristics of 10E75 glass plates with this system. A Macbeth Quantalog Sensitometer filtered with a 10 Å bandpass filter centered at 6328 Å was used to expose calibrated step wedges onto the plates. After nitrogen burst processing, the density of the wedges was read with diffuse white light using a Macbeth Quantalog Densitometer. The resulting density vs. logarithm of exposure (D-Log E) curves for identical plates showed an apparent spread of gamma values from approximately 5.5 to 7.0. This spread seemed unreasonably large, but extensive checks showed no problems with the sensitometer. Several plates were then exposed to a simulated point source* and processed in the nitrogen burst system. Almost every plate exhibited a density gradation from one corner, which had the lowest density, to the opposite corner where the highest densities were found. The nitrogen burst system was now suspect. Additional plates were exposed to the simulated point source and processed, emulsion up, in an open tray with agitation from a soft camel hair brush. The same density gradations persisted. After the many tests, we are unable to attribute these density gradations to anything but variations in the emulsions themselves. With point source illumination to produce a plate with nominally an optical

*The plates were exposed to a #1493 incandescent lamp placed normal to, and six feet from the emulsion surface.

density of 4 (O.D. 4), the variations from corner-to-corner would be on the order of O.D. 0.6. The average variation from the center of one plate to another was considerably less (O.D. 0.3). After the sensitometric tests, the density gradations implied that more repeatable results would be obtained with only one hologram in the center of each plate. Indeed, all data were recorded in this manner.

Step wedges recorded on a plate with variations as described above will produce different D-Log E curves depending upon the orientation of the exposed wedges with respect to the low and high density corners. It is therefore assumed that the gamma data which originally caused us concern were accurate and represent the spread in D-Log E data to be expected when a step wedge is recorded with random orientation on these 10E75 plates.

All data plates were developed in D-19 at 68°F for 5 minutes with a 1 second nitrogen burst agitation every 8 seconds. This was done to approximate the processing conditions used for the study of amplitude holograms in reference 1.

Figure 1. The family of D-Log E curves for a randomly oriented step wedge recorded on Agfa 10E75 glass plates of lot #574918 when processed in D-19 at 68°F for 5 minutes with nitrogen burst agitation.

The complete processing sequence was:

Development	5 minutes
Kodak Indicating Stop Bath	30 seconds
Kodak Rapid Fixer	5 minutes
Water wash	10 minutes
Kodak Photo-Flo	30 seconds
Dry with room temperature air	2 minutes

The plates used were of lot #574918. The corresponding D-Log E data for these plates is illustrated in Figure 1. Measurement with laser light would give results showing higher gammas, but since no quantitative gradient calculations were to be attempted, the small corrections due to laser illumination were not warranted.

Hologram Recording and Measurement Arrangements

The setup used to record diffuse holograms is shown in Figure 2. The object, a 1951 Air Force resolution chart, was centered 160mm from the holographic plate and diffusely illuminated by an expanded and collimated laser beam (apertured by A_2)

Figure 2. The setup used to record diffuse holograms is illustrated. The shutter (S) was used to control the exposure time. The mirrors (M_1 , M_2 , M_3 and M_4) and beamsplitter (BS) were used to direct the He-Ne laser beam to the reference and object beam collimators (L_3 - L_4) and (L_1 - L_2), respectively. Aperture A_1 and A_3 are pinhole filters used to increase the spatial coherency of the beam. Aperture A_2 was used to restrict the object beam to the diffuser (D) thus eliminating extraneous light at the hologram plate (H). The object (O) was centered relative to H and placed 160mm away. The ground glass diffuser (D) was 20mm from the object. The reference beam was expanded to a 100mm diameter and offset by an angle $\theta = 16^\circ$.

striking a ground glass (D). An alternate method (for recording focused image holograms) was to insert a lens (not shown) to form an image of O on the plate located at H. The reference beam was always an expanded and collimated bundle 100mm in diameter impinging onto the plate at an offset angle (θ) of 16 degrees relative to the plate normal. The spatial frequency of the recorded unmodulated fringes was nearly 440 lp/mm. The laser used was a Spectra-Physics model 125A with an intercavity etalon resulting in single frequency TEM_{00} operation. The path length difference of the beams was less than 1 cm. The plate holder (H) was constructed to allow the plate to be rotated in its own plane for recording multiple exposure holograms. Additional components of the setup are described in the figure caption.

After the plates were processed, their diffraction efficiencies were measured by returning them to the holder (H). Figure 3 illustrates the apparatus used to measure diffraction efficiency. The object beam was blocked and the reference beam was mechanically chopped before L_3 to allow AC measurements with a photomultiplier tube (PM). The reference beam was doubly apertured by A_4 and A_5 to allow measurements of a small area with constant optical density. This area was 10mm in diameter for diffusely recorded holograms and 20mm for the less efficient focused image holograms. An 88mm focal length lens (L_5) was used to

focus the virtual image onto the PM face for measurement of the reconstructed energy (I_r). Transmitted reference beam intensities (I_t) were measured by moving the PM to position 2. Incident reference beam intensity (I_0) was measured by removing the plate. Diffraction efficiency (η) is then defined as I_r/I_0 . Optical density of the plates can be calculated from I_t and I_0 .

Figure 3. The setup used to measure the diffraction efficiency is illustrated. The reference beam was restricted by two apertures (A_4 and A_5). Lens L_5 imaged the virtual image onto the photomultiplier (PM) tube at position #1. The PM was moved to position #2 to measure the incident intensity.

The signal-to-noise ratio (S/N) of virtual images was measured by removing L_5 and inserting L_6 , a 172mm focal length lens which magnified the reconstructed image approximately 10 times (see Figure 4). The focused, magnified image in Plane I was sampled with the PM apertured to a 10mm diameter by A_6 . S/N was defined as the ratio of energy in Section A to that in Section B, both of which are illustrated in Figure 5. When the S/N of a real image was measured, the hologram at H was rotated 180° , forming a real image to the right of H. Lens L_6 was then moved to form a 10X magnified image on a second Plane I' to the right of Plane I (not shown).

Resolution measurements were taken by replacing the 10mm diameter A_6 in Figure 4 with a scanning slit. The resolving power of L_6 was large enough so as not to be the limiting element of the system. The PM output of the scanning slit system was recorded on a strip chart recorder, and visibility data were calculated for the groups of bars of interest. Slit dimensions were chosen as approximately one-half the width and height of the smallest bar being measured.

Figure 4. The apparatus used to measure signal-to-noise ratio (S/N) is depicted. Apertures A_4 and A_5 restrict the reference beam to the size used for efficiency measurements. Lens L_6 images the reconstructed virtual image onto Plane I where the PM apertured by A_6 measures the signal in position 1 and noise in position 2. If the S/N of the real images is desired the plate is rotated 180° in H and L_6 is moved to again form an image at a Plane I' , located to the right of I.

Figure 5. The position of the 10mm diameter aperture relative to specific positions in the image at Plane I in Figure 4 is illustrated. Section A is located in the large square between Group 0 and 1 and Section B is between element No. 4 of Group 0 and elements Nos. 3-5 of Group 2.

Determination of "Best" Bleach

Five sets of single exposure holograms were exposed and processed identically with a reference-to-object beam ratio (K) of 1. The developed densities ranged from O.D. 0.4 to 3.95. The η of each set was measured as well as S/N of one set. Each set of plates was then bleached in one of the five selected bleaches described below.

Bleach 1: 10 gr/l potassium ferricyanide

Bleach	7 minutes
Water wash	5 minutes
200° ethyl alcohol	2 minutes
Dry in moving room temperature air	2 minutes

Bleach 2: 10 gr/l mercuric chloride

Bleach	5 minutes
Water wash	5 minutes
200° ethyl alcohol	2 minutes
Dry in moving room temperature air	2 minutes

Bleach 3: 50 gr/l cupric bromide

Kodak Hardener SH-5	3 minutes (Optional Step)
Water wash	6 minutes
Bleach	7-1/2 minutes
Water wash	5 minutes
Clearing bath ¹³	3 minutes
Water wash	5 minutes
200° ethyl alcohol	2 minutes
Dry in moving room temperature air	2 minutes

Bleach 4: Bromine vapor

Plates were suspended emulsion down over a pool of liquid bromine in a closed glass jar. Approximately 110 grams of bromine with a surface area of $2.5 \times 10^{-2} \text{ m}^2$ was used for bleaching. 20 to 30 minutes in the vapor were required to remove all the silver from the denser plates. After bleaching, the plates remained in the moving air of a fume hood for 3 days to remove any outgassing bromine vapors.

Bleach 5: Kodak Chromium Intensifier

Part A	3 minutes
Water wash	30 seconds
Part B	2 minutes
Water wash	5 minutes

200° ethyl alcohol

2 minutes

Dry in moving room temperature air 2 minutes

It was not known whether the SH-5 used as a prehardener for Bleach 3 was actually needed. For these initial tests, Bleach 3 was used without a hardener to evaluate the cupric bromide portion of the process. A visual inspection of the reconstructed images revealed that the virtual images for all plates were nearly obliterated by scattered noise around the image. It was noticed that the S/N for the real image was larger than for the virtual image. Also, the S/N seemed to improve with radial distance from the plate center. The η and S/N measurements of the real image were taken at a point 18mm from the center of the plate to take advantage of the increased S/N. The numbers so obtained should be a valid comparison of the five bleaches, but comparisons to the virtual image parameters before bleaching is difficult. The real image data obtained are shown in Figures 6 and 7, along with the before-bleach data for rough comparisons.

Figure 6. Reconstruction efficiencies of five series of single exposure holographic plates before and after bleaching in five different bleaches. Note that different images have been measured. (See text).

Figure 7. Signal-to-noise of five series of single exposure holographic plates before and after bleaching in five different bleaches. Note that different images have been measured. (See text).

Bleach 3 without hardener produced both the highest η and best S/N of any of the five bleaches tested. The bleached $K=1$ plates, even for Bleach 3, produced virtual images which were definitely unusable for any data analysis because $S/N \rightarrow 0$. The real images, although usable, were extremely noisy.

Bleach 3 Results

Reference beam energy was fairly uniform over the center 50mm of the hologram plate, while the object beam energy decreased rapidly off axis. The fact that S/N improved with radial distance from the plate center even though densities were comparable indicated that larger S/N values should be obtained with larger K values.

Single Exposure Holograms -- Figures 8 and 9 illustrate the η and S/N, respectively, before and after the bleach of single exposure holograms bleached without hardener. The K values were varied from 1 to 95, corresponding to a modulation index range of 1.0-0.2. Theoretically,^{1,2,3} the lower the modulation index, ρ , the lower η . Except for the highly nonlinear recording case of bleached $K=1$, this was found to be true. In fact, at densities

Figure 8. Diffraction efficiency vs. before bleaching optical density of various K values of single exposure holograms bleached in bleach 3 with no hardener. (Virtual image data).

Figure 9. Signal-to-noise vs. before bleaching optical density for various K values of single exposure holograms bleached in bleach 3 with no hardener. (Virtual image data).

above 1.5 the lower modulation $K=4$ hologram gave greater bleached η than did those with $K=1$. S/N values increased with increasing K values for both amplitude and bleached cases except for $K=95$. At this low modulation ratio ($\rho = 0.2$), the efficiency is so low that normal scattered plate noise degrades the S/N. All additional single exposure holograms were recorded with $K=9$ ($\rho = 0.6$). This allowed a bleached η of 10% with an S/N = 20 for a complex resolution chart object.

Since all the above results were for hologram without hardener, two additional series of plates were exposed. One series was processed with no hardener; the second was pre-hardened in SH-5 for 3 minutes before development. Both were single exposure, $K=9$. The effective speed of 10E75 plates decreases proportionately to the length of prehardening time. Lehmann,¹³ et. al., determined 3 minutes to be a reasonable compromise between speed, efficiency, and signal-to-noise ratio. Figures 10 and 11 represent the results of this test. The six points of the nonhardened curve represent the same initial exposure energy as the

Figure 10. Virtual image diffraction efficiency before and after bleaching in bleach 3 both with and without SH-5 hardener before development.

Figure 11. Signal-to-noise ratio of the virtual image before and after bleaching in bleach 3 both with and without SH-5 hardener before development.

six lower density points of the hardened curve. The exposure producing a density of 2.77 without hardening gives only a density of 1.35 with three minutes of prehardening. After bleaching, the η of the hardened plates was 1/2 to 1/3 less than for the nonhardened ones, but the S/N was approximately doubled. Similar η can be achieved with a nonhardened K=23 plate, but the S/N for such a bleached plate would be near 40 (Figure 9), while for this hardened and bleached K=9 plate it is near 60. In fact, for the lowest density hardened plate (O.D. 0.36) the bleached S/N was larger than the unbleached. The SH-5 is definitely useful if increased S/N at the expense of efficiency and sensitivity can be justified. It was found that the use of the hardener after the development step, but before bleaching, does not affect sensitivity but produced bleached results identical to those using no hardener.

Multiple Exposure Holograms -- The properties of multiple exposure holograms were

measured and are shown in Figures 12 and 13. The two-exposure holograms were recorded with a 90° rotation of the plate about its normal between exposures. The four-exposure plates were rotated 45° between each exposure. This allowed the virtual and real image reconstructions from all holograms to be spatially separate for measurement. The K values given are for each individual exposure. The 4 at 45° , K=4 plates were made by superimposing four identical K=4 gratings on the same plate area. The equivalent modulation index (ρ') of the grating for any one hologram has been calculated assuming all other holograms act solely as post- or pre-exposure fog levels.¹ As expected, η decreases as ρ' decreases (Figure 12). At the higher densities, there is as much as a thousand fold increase in η after bleaching.

Figure 12. Diffraction efficiency of the first recorded virtual image of single and multiple exposure holograms of various K values before and after bleaching in bleach 3 without the use of a prehardener.

Figure 13 illustrates the multiple exposure S/N of the first recorded virtual image. If it were truly valid to treat the extra exposures simply as background fog, the curves would be similar to those of Figure 9 with respect to their ρ' dependence. Although estimation of

Figure 13. Signal-to-noise ratio of the first recorded virtual image of single and multiple exposure holograms of various ratios before and after bleaching in bleach 3 without the use of a prehardener.

the bleached multiple exposure S/N is not as simple as calculating the effective ρ and comparing it to the single exposure results, some parallels can be drawn. The S/N of $K=4$ gratings were larger than for the corresponding $K=1$ case, and the S/N of a four-exposure plate was greater than for a similar two-exposure one. In both these cases, a decrease in ρ' results in an increase in S/N.

Focused Image Holograms -- Some of the holographic data being recorded at Sandia Laboratories are double exposure interferograms recorded with an image of the object focused on the holographic plate surface. Since these holograms are considerably different from the diffusely recorded Fraunhofer type holograms studied above, additional data were collected. Referring to Figure 2, only optical components D and O were disturbed. D and O were moved away from the plate, giving an O to H distance of 525mm. A Schneider-Kreuznach Componon 28mm focal length $f/4$ enlarger lens was inserted between O and H, resulting in a 16X magnified

image of O focused at H. In the diffuse hologram case, K is easy to measure because both beams have a fairly uniform energy distribution near the plate center. With a focused image hologram, the object beam for a resolution chart has energy only in the areas corresponding to the bright bars in the object. To determine K , the object beam intensity was measured in the large square referred to as Section A in Figure 5 and compared to the reference beam. Since areas of the object beam are dark, these areas of the developed hologram will have no grating and will not contribute energy to the reconstructed image. Because of the large amount of dark areas in the resolution chart image, it was expected that η would be considerably lower than for the diffuse case. The experimental results are shown in Figures 14 and 15. The η plots of Figure 14 look much like the corresponding diffuse object data of

Figure 14. Diffraction efficiency of the first recorded virtual image of single and multiple exposure focused image holograms with a magnification ratio of 16 before and after bleaching in bleach 3 with no prehardener.

Figure 12 except the η 's are approximately one order of magnitude less. The strikingly different data were the S/N of Figure 15. Both before and after bleaching, the S/N data for

the focused image holograms show considerable scatter, but two trends were still very evident. The S/N of the amplitude focused image plates was considerably less than the corresponding diffuse image plates. Typically, bleaching increased the S/N for every focused image plate by a factor of 2 to 3. Only two very low density (O.D. < 0.4) diffuse object holograms showed any increase in S/N after bleaching. The usual diffuse hologram result was a drastic reduction of S/N after bleaching. Also it should be noted that for the diffuse case, $K=4$ gave larger S/N both before and after bleach than a $K=1$, while for focused image holograms the reverse was true. These major differences indicate that a ratio other than 9 might be optimum for focused single or multiple exposure holograms.

Figure 15. Signal-to-noise ratio of the first recorded virtual image of single and multiple exposure focused image holograms with a magnification ratio of 16 before and after bleaching in bleach 3 with no prehardener.

Resolution Measurements -- A scanning slit and photomultiplier system was used to measure the resolution of the reconstructed virtual images of the holograms before and after bleaching. Resolution did not appear to be a function of density for any of the holograms.

The result for single exposure holograms with $K=9$ is shown in Figure 16. If a fringe visibility criterion of 0.5 is used as the limit of resolution, the unbleached focused plates produced approximately 100 lp/mm. The actual 16X image of the lens was also scanned and it

Figure 16. Resolution measurements of single exposure diffuse and focused object holograms before and after bleaching in bleach 3. All plates were with $K=9$.

found that in He-Ne light the $f/4$ lens itself was only capable of 100 lp/mm; thus, the measured resolution was limited by the lens and not the holograms. The interesting thing is that after bleaching the resolution appears to increase to near 115 lp/mm. This is probably due to the increased S/N after bleaching for these focused image holograms. The diffusely recorded holograms were reconstructed using a 10mm reference beam corresponding to an $f/16$ system. The use of a prehardener did not affect the resolution of these plates either before or after bleaching. There was considerable scatter in the data, but the 0.5 criterion resulted in a resolution of 45 lp/mm, which was essentially unchanged by bleaching.

Resolution data for multiple exposure holograms are shown in Figure 17. The four-exposure $K=1$ focused image holograms seemed to be unaffected by bleaching. Their resolution at a visibility of 0.5 was 100 lp/mm. The $K=4$ multiple exposures seemed to be 100 lp/mm before bleaching but 115 lp/mm afterward, similar to the single exposures. The diffusely

recorded four-exposure holograms also gave mixed results. It seemed the diffuse K=4 holograms were unaffected by bleaching. The resolution was 38 lp/mm. The K=1 plates, on the other hand, seemed to improve with bleaching. While none of the unbleached diffuse multiple exposure K=1 measurements exceeded a visibility of 0.5, an extrapolation of the data would give $\ll 20$ lp/mm. After bleaching, these plates gave nearly 38 lp/mm. Scatter in the data for the diffuse, multiple holograms did not allow accurate determinations. Comparisons of the resolution of the first and fourth recorded holograms showed no significant differences.

Figure 17. Resolution measurements of multiple exposure diffuse and focused object holograms before and after bleaching in bleach 3.

Alcohol Bath and Aging Affects -- Even though a final drying process involving an alcohol bath had been suggested as a way to improve S/N,^{11,12} our reason for using an alcohol bath was to speed up the drying process considerably. Two to three months after the various holograms had been bleached, η and S/N were again measured. The plates were then rewashed in successive baths of ethyl alcohol, water, and ethyl alcohol, and η and S/N were remeasured. The first rewash in alcohol seemed not to affect either parameter. The second water bath seemed not to affect S/N, but decreased η on the order of 20%. The third alcohol

bath did not restore the efficiency lost in the water wash. The water bath irreversibly degraded η while leaving S/N unchanged.

The more surprising result seemed to be that the bleached holograms, even though stored in subdued light, had lower η 's even before a water bath.

Several series of plates were remeasured. The η 's of amplitude holograms were similar to earlier results, but the bleached ones had decreased appreciably. It seemed the longer the plates had been bleached, the lower η became. Figure 18 illustrates this phenomenon.

Figure 18. Diffraction efficiency degradation of two series of plate with age.

V. Conclusions

The bleach judged to give the best performance with 10E75 plates was the cupric bromide suggested by Lehmann, et. al. The Kodak SH-5 prehardener was very effective in increasing S/N but at the expense of emulsion speed and diffraction efficiency. We determined that the extra loss in speed would outweigh the advantages for our purposes and did not use the SH-5

in the remainder of our tests.

For a bleached diffuse hologram, it was confirmed that S/N increases with increasing K values (at least below 23) but decreases with increasing optical density before bleaching. Extremely high efficiencies were accompanied by low S/N. However, intermediate bleached diffraction efficiencies considerably higher than amplitude cases can be produced with good S/N by selecting the appropriate parameters (see Figures 8 and 9). An optimum bleached hologram would seem to be one with a developed density, before bleaching, of from 1.5 to 2.0.

Multiple exposure diffuse holograms were found to be very similar to single exposures when bleached. S/N decreased with increasing density, but increased with increasing K value. Optimum density was in the 1.5 to 2.0 range, as with the single exposures.

A surprise was the bleached focused image holograms which showed not only increased efficiency but increased S/N when compared to the unbleached state. They also appeared to have an optimum before bleach density of 1.5 to 2.0.

Resolution measurements indicated that, at the worst, bleaching leaves the resolution unchanged; there were several cases where the resolution determined by an image visibility criterion of 0.5 seemed to improve with bleaching.

Stability of the bleached plates is still an area for concern. The diffraction efficiency of these hologram plates seemed to decrease with age when no great amounts of light are used. Further study in this area might be desirable.

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