PROCEEDINGS OF SPIE
SPIE—The International Society for Optical Engineering

Holographic Materials IV

T. John Trout
Chair/Editor

27 January 1998
San Jose, California

Sponsored by
SPIE—The International Society for Optical Engineering
IS&T—The Society for Imaging Science and Technology

Published by
SPIE—The International Society for Optical Engineering

Volume 3294

SPIE is an international technical society dedicated to advancing engineering and scientific applications of optical, photonic, imaging, electronic, and optoelectronic technologies.

The papers appearing in this book comprise the proceedings of the meeting mentioned on the cover and title page. They reflect the authors' opinions and are published as presented and without change, in the interests of timely dissemination. Their inclusion in this publication does not necessarily constitute endorsement by the editors or by SPIE.

Please use the following format to cite material from this book:

Author(s), "Title of paper," in *Holographic Materials IV*, T. John Trout, Editor, Proceedings of SPIE Vol. 3294, page numbers (1998).

ISSN 0277-786X
ISBN 0-8194-2734-9

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone 360/676-3290 (Pacific Time) • Fax 360/647-1445

Copyright ©1998, The Society of Photo-Optical Instrumentation Engineers.

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is \$10.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at <http://www.directory.net/copyright/>. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher. The CCC fee code is 0277-786X/98/\$10.00.

Printed in the United States of America.

Highly nonlinear characteristics of bleached holograms recorded in Agfa 8E75HD plates

István Bányász^a, Augusto Beléndez^b and Antonio Fimia^a

^a Laboratorio de Optica, Departamento Interuniversitario de Optica
Universidad de Alicante, Apdo. 99, E-03080 Alicante, Spain

^b Departamento de Ingeniería de Sistemas y Comunicaciones
Universidad de Alicante, Apdo. 99, E-03080 Alicante, Spain

ABSTRACT

A novel method for the characterisation of the processing of both absorption and phase holograms was proposed. Differently from the previous models, the square root of the diffraction efficiency of the processed hologram was directly related to the amplitude of the optical density modulation obtained at the development step. This characteristic is a good indicator of the degree of nonlinearity of the hologram processing. While the Lin - functions of phase holograms are similar to those of absorption holograms, the shape of the proposed function is completely different. Optical density and diffraction efficiency of holograms recorded in Agfa-Gevaert 8E75HD plates and processed with AAC developer and a solvent bleach without fixation step were measured and used for the demonstration of the method.

Keywords: silver halide materials, nonlinear holographic recording, bleached holograms

1. INTRODUCTION

It is well known that processing can greatly affect the quality of the holograms. To evaluate the effects of the recording material and the processing on the reconstructed image, a great number of methods have been proposed and used¹⁻¹⁰. One of the most important property of holographic recording is the degree of its linearity. In the greatest part of the early papers on holographic recording materials the density against exposure or the amplitude transmittance against exposure functions were used for the evaluation of the imaging properties of the nonlinearly recorded holograms. Some authors derived other characteristics from the above functions, like Biedermann⁸, Pennington and Harper⁹ and Kaspar *et al.*¹⁰. Pennington and Harper⁹ proposed the use of the optical density difference against average optical density function for characterizing the recording of silver halide absorption holograms. Lin proposed the use of the square root of the diffraction efficiency against bias exposure and fringe visibility function of plane wave holograms (See e.g. in Ref. 11).

The characterization of bleached silver halide holograms is more complicated since their processing involves the conversion of the initial absorption grating into a phase one. In the greatest part of the experimental and theoretical works either the Lin-curves were used or the diffraction efficiency was related to the average optical density before bleaching¹²⁻¹⁴. Other methods, such as relating the square root of the diffraction efficiency of the phase grating to the effective electrical polarizability of the silver salt molecules¹⁵ or the refractive index modulation to the optical density modulation¹⁶ were also used. However, the direct measurement of the refractive index modulation across the hologram by interference microscopy can be applied only for gratings of low spatial frequency¹⁷.

A method for the evaluation of the effects of film nonlinearities on the image reconstructed from absorption holograms has been developed by one of the authors of the present work¹⁸. That method made use of the Lin - functions of silver halide materials. In an other work Lin - functions of the Agfa-Gevaert 8E75HD for processing with two different developers were measured and used for the theoretical and experimental evaluation of the quality of the reconstructed image¹⁹.

The aim of the present work was to characterize the processing of phase holograms. To accomplish this task, we related the square root of the diffraction efficiency of the final hologram to the amplitude of the density modulation before bleaching. We think that this function describes better the processing of the holograms than those mentioned in the previous paragraph. The difference in these characteristics of absorption and phase holograms was also demonstrated.

2. EXPERIMENTS

We recorded two series of plane wave holograms in Agfa-Gevaert 8E75HD with a Helium - Neon laser operating at 632.8 nm. The interbeam angle was 45°. Hologram pairs at seven values of fringe visibility, namely at $V=0.2, 0.4, 0.6, 0.8, 0.9, 0.95$ and 1.0 have been recorded. Twelve hologram pairs at exposures ranging from $10 \mu\text{J}/\text{cm}^2$ to $1.6 \text{ mJ}/\text{cm}^2$ have been recorded at each visibility. Care was taken to maintain the same intensity ($400 \mu\text{J}/\text{cm}^2 \pm 1\%$) at recording to minimize the effect of reciprocity failure.

One element of each pair of holograms has been developed with AAC developer (3 minutes at 20 C°) and fixed with Kodak F24 fixer. The composition of the AAC developer was the following:

Ascorbic acid	18 g/litre
Sodium carbonate	120 g/litre.

The other element of the hologram pair has also been developed by AAC, and has been bleached in a R9 solvent bleach without a fixation step. Its composition was as follows:

Sulphuric acid (96-98%, purissimum)	10 ml/litre
Potassium dichromat	2 g/litre

Bleaching has been terminated 1 minute after the plate became transparent.

Fig. 1 Measured (points) and fitted (solid line) $D(E)$ function of Agfa-Gevaert 8E75HD, phase holograms recorded at a $V=0.2$, and developed by AAC. See parameters of the fitted function in the text.

Fig. 2 Measured (points) and fitted (solid line) $D(E)$ function of Agfa-Gevaert 8E75HD, for absorption holograms recorded at a fringe visibility of 0.2 and developed by AAC. See parameters of the fitted function in the text.

After processing all the holograms, optical density of the absorption ones and diffraction efficiency of the phase ones have been measured. Both optical density and diffraction efficiency were corrected for reflection losses. Measured density against exposure data are shown in Fig. 1, along with an analytical function fitted to them (that will be described in the next section). Square root of the diffraction efficiency of the phase holograms against exposure is shown in Fig. 3, also along with a fitted analytical function.

For the characterization of the absorption holograms we used our previous results¹⁸. The measured density against exposure data are shown in Fig. 2, along with an analytical function fitted to them. The Lin - functions of the absorption holograms are shown in Fig. 4, also along with a fitted analytical function.

Fig. 3 Measured (points) and fitted (solid lines) $\sigma(E_0, V)$ curves of Agfa-Gevaert 8E75HD, for phase holograms processed by AAC developer and R9 bleach. Visibilities are indicated in the figure.

Fig. 4 Measured (points) and fitted (solid lines) $\sigma(E_0, V)$ curves of Agfa-Gevaert 8E75HD, for absorption holograms developed by AAC. Visibilities are indicated in the figure.

3. CHARACTERISATION OF THE BLEACHING PROCESS

In order to make it possible to extract the desired characteristics from our measurements, we fitted analytical functions both to the measured density against exposure and square root of diffraction efficiency against exposure functions.

Although several analytical approximations of the density vs exposure curves of silver halide holographic recording materials can be found in the literature^{20,21}, we used a slightly improved version of a relatively simple function introduced by us¹⁹:

$$D(E_0) = -2 \log \left[\frac{t_0}{\left(\frac{E_0}{E_1}\right)^\kappa + 1} + t_1 \right] \quad (1)$$

where D is the optical density, E_0 is the bias exposure, and t_0 , E_1 , κ and t_1 are parameters.

Fits made by this function to measured data are shown in Figs. 1 and 2. The parameters of the first one are: $t_0 = 0.75$, $E_1 = 37.5 \mu\text{J}/\text{cm}^2$, $\kappa = 2.15$ and $t_1 = 0.0075$ and for the second one $t_0 = 0.97$, $E_1 = 20.0 \mu\text{J}/\text{cm}^2$, $\kappa = 2.23$ and $t_1 = 0.002$. The visibility of the interference fringes was in both cases $V = 0.2$. The $D(E_0)$ function is slightly different for gratings recorded at different fringe visibilities, and this was taken into account in our calculations.

We fitted the following analytical function¹⁸ to the measured square root of diffraction efficiency against bias exposure and fringe visibility [$\sigma(E_0, V)$] curves:

$$\sigma(E_0, V) = f(E_0) (1 - e^{-V}) e^{-\frac{[V - V_0(E_0)]^2}{w^2(E_0)}} \quad (2)$$

where σ is the square root of the diffraction efficiency, E_0 is the bias exposure, V is the visibility of the interference fringes and $f(E_0)$, $V_0(E_0)$ and $w(E_0)$ are parameter functions of the following form:

$$\begin{aligned} Par(E_0) = & c_{i01} \left[\frac{1}{\exp\left(\frac{c_{i11} - E_0}{c_{i12}}\right) + 1} + c_{i13} \right] \left[\frac{1}{\exp\left(\frac{E_0 - c_{i21}}{c_{i22}}\right) + 1} + c_{i23} \right] \cdot \\ & \cdot \left[\frac{1}{\exp\left(\frac{c_{i31} - E_0}{c_{i32}}\right) + 1} + c_{i33} \right] \end{aligned} \quad (3)$$

where "Par" stands for f , V_0 and w , and c_{ixx} represent three sets of constants ($i=f, V_0, w$).

Fits of the above function to the experimental data can be seen in Figs. 3 and 4. The former corresponds to the phase holograms processed by AAC developer and solvent bleach without a fixation step and the latter to absorption holograms

developed by AAC . Visibility of the recording interference patterns is indicated in the figures. The parameters of the fitted function for the absorption holograms have been published in a previous paper ¹⁹. The parameters of the $\sigma(E_0, V)$ function for the phase holograms are shown in Table I. Fitting an analytical function of two variables and 30 parameters to the experimental data was a tedious work, nevertheless it allowed us to handle the data easily and construct the desired $\sigma(\Delta D)$ function (i.e. the square root of the diffraction efficiency against the amplitude of the density modulation).

Indices (xx)	c_{fxx}	$c_{(V_0)xx}$	c_{wxx}
01	1.5	3.0	3.0
11	38	72	20.5
12	32	2.5	3.0
13	0	0.21	0.95
21	675	53.5	700
22	300	2.8	120
23	0	0.15	0.27
31	12.5	28	4
32	3.2	-1.8	-21
33	0	1.64	0.14

Table I Table I. Parameters of the $\sigma(E_0, V)$ function of Agfa-Gevaert 8E75HD, processed by AAC developer and R9 solvent type bleach.

We determined the parameters of the $\sigma(E_0, V)$ function in the following way: First we fitted the $\sigma(E_0, V)$ function (2) to all the twelve measured $\sigma(V)$ curves ($E_0 = \text{constant}$). It has been accomplished by using standard programs for the nonlinear fitting. Since there were only three parameters (f, V_0 and w) to be determined for each curve, it could be done by high precision. Afterwards, we fitted the $Par(E_0)$ function (3) to the $f(E_0)$, $V_0(E_0)$ and $w(E_0)$ curves obtained in the previous step. Since there were ten parameters to be determined in each case, we had to rely on our previous experience in fitting the same function to experimental data to assign adequately narrow ranges to the initial values of the parameters. Finally we obtained a set of parameters that describes well the measured function, although, naturally is not unique.

Evaluation of the $\sigma(\Delta D)$ function from Eqs. (1) and (2) is straightforward.

If E_0 is the bias exposure and V the fringe visibility, the minimum ($E_{\min}$) and maximum ($E_{\max}$) exposures can be expressed as follows:

$$E_{\min} = E_0 (1 - V) \quad (4)$$

$$E_{\max} = E_0 (1 + V) \quad (5)$$

Consequently, the amplitude of the density modulation at a bias exposure of E_0 and visibility of V is:

$$\Delta D(E_0) = D(E_0 \cdot (1 + V)) - D(E_0 \cdot (1 - V)) \quad (6)$$

Now, since both ΔD (Eq. 6) and σ (Eq. 2) are expressed as functions of the bias exposure and fringe visibility, the desired $\sigma(\Delta D)$ graphs can be evaluated.

Square root of the diffraction efficiency as a function of the amplitude of the density modulation for both absorption and phase holograms is shown in Fig. 5. The characteristics of the amplitude holograms can be seen in the first column and those of the corresponding phase holograms (recorded under identical conditions) in the second one. Fringe visibility at recording is indicated right to each row. While the $\sigma(E_0, V)$ functions (Figs. 3 and 4) of the two types of hologram are of similar shape, the difference in their $\sigma(\Delta D)$ characteristics is striking.

Since absorption holograms were exposed only up to $50 \mu\text{J}/\text{cm}^2$, ΔD is monotonically increasing up to about 2.1, and there is no turning point in the graph, i.e. only one value of σ belongs to each value of ΔD . Moreover, the shape of the $\sigma(\Delta D)$ characteristics of the absorption holograms is similar at each fringe visibility, namely an incomplete arch, somewhat resembling to the $\sigma(E_0, V)$ function of the material.

The $\sigma(\Delta D)$ characteristics of the phase holograms are completely different. Since they were exposed up to the density saturation ($1500 \mu\text{J}/\text{cm}^2$), the initially monotonically increasing amplitude of the density modulation is decreasing beyond a certain bias exposure (except at $V=1$), so there is a turning point in the characteristics. The ΔD value corresponding to the turning point varies between 0.6 ($V = 0.2$) and 3.7 ($V = 0.95$). The value of E_0 belonging to these amplitudes of the density modulation is between $105 \mu\text{J}/\text{cm}^2$ ($V = 0.2$) and $290 \mu\text{J}/\text{cm}^2$ ($V = 0.95$). As mentioned before, there is no turning point at $V = 1.0$. The turning points are around the maxima of the $\sigma(E_0, V)$ function, as can be seen in Fig. 4.

The $\sigma(\Delta D)$ curves at each visibility follow a more or less straight line with a quasi uniform slope (ranging from 0.25 to 0.3) almost up to the turning point. The second part of the graphs (after the turning point) is not straight. At the visibilities $V = 0.2$ and 0.4 it crosses twice the first part forming two loops (hardly seen in the figure). The figure suggests that the falling part of $\sigma(\Delta D)$ nearly retraces the rising part between $V = 0.7$ and 0.8 , so best linearity over the whole exposure range can be achieved in that visibility range. However, there can be seen a pronounced dip in the graphs that is discernible from $V = 0.8$ on. We found that the minimum of the dip corresponds to a bias exposure $E_0 = 70 \mu\text{J}/\text{cm}^2$, i.e. about the inflexion point of the $D(E_0)$ curves (See Fig.1).

Fig. 5 Square root of the diffraction efficiency of absorption (left column of graphs) and phase (right column) holograms vs. the amplitude of the density modulation. Fringe visibility is indicated on the right.

4. DISCUSSION AND CONCLUSIONS

On the basis of measurements and an empirical model, we evaluated the $\sigma(\Delta D, V)$ characteristics of a silver halide holographic recording material processed to obtain amplitude and phase holograms. We found that the characteristics of the amplitude holograms were of similar shape at any fringe visibility, and they cannot be considered to be globally linear. On the other hand, the rising part of those characteristics of the phase holograms was quasi linear (with an average slope between 0.25 and 0.3) even at high fringe visibilities. Contrary to the curves for the absorption holograms, the $\sigma(\Delta D)$ curves of the phase holograms make one or more loops. It is surprising that it is around visibility 0.8 where the two branches of the $\sigma(\Delta D)$ curve are *relatively* the closest to each other and there the relationship between σ and ΔD , at least in the upper branch, is quasi linear. A dip belonging to the inflexion point of the $D(E_0)$ curve was also found in the characteristics of the phase holograms.

The above method was intended to serve as a tool for practical holographers, and not to compete with the existing theoretical models of holographic recording materials. However, further refinement of it on the basis of higher order coupled wave theory seems to be feasible. A first step might be to perform a Fourier- analysis of the initial density modulation and to relate the square root of the diffraction efficiency of the final phase grating to the amplitudes of its harmonics (instead of its full amplitude).

5. ACKNOWLEDGEMENT

This work has been carried out in the framework of a scholarship granted to I. Bányász by the Spanish Ministry of Education and Scientific Research.

6. REFERENCES

- 1 A. A Friesem and J. S. Zelenka, "Effects of film nonlinearities in holography", *Appl. Opt.*, **6**, 1755-1759, (1967)
- 2 J. W. Goodman and G. R. Knight, "Effects of film nonlinearities on wavefront-reconstruction images of diffuse objects", *JOSA*, **58**, 1276-83, (1968)
- 3 G. R. Knight, *Appl. Opt.*, vol. 7, 205, (1968)
- 4 A. A. Friesem, A. Kozma and F. G. Adams, "Recording Parameters of Spatially Modulated Coherent Wavefronts", *Appl. Opt.*, **6**, 851-56, (1967)
- 5 J. C. Wyant and M. Parker Givens, "Effects of Photographic Gamma on Hologram Reconstruction", *JOSA*, **59**, 1650-58, (1969)
- 6 F. J. Tischer, *Appl. Opt.*, vol. 9, No 6, p 1369, (1970)
- 7 Yu. N. Denisyuk et al, *Optika i Spectroscopiya*, vol. 29, 994, (1970), (in Russian)

- 8 K. Biedermann, "A Function Characterizing Photographic Film that Directly Relates to Brightness of Holographic Images", *Optik*, **28**, 160-76, (1968)
- 9 K. S. Pennington and J. S. Harper, "Techniques for Producing Low-Noise, Improved Efficiency Holograms", *Appl. Opt.* **9**, 1643-50, (1970)
- 10 F. G. Kaspar, R. L. Lamberts and C. D. Edgett, "Comparison of Experimental and Theoretical Holographic Image Radiance" *JOSA*, **58**, 1289-95, (1968)
- 11 R. Collier, K. Burckhardt and L. Lin, *Optical Holography* (Academic Press, New York, (1971), Chaps. 10 and 12.
- 12 H. T. Buschmann, "Bleichprozesse zur Erzeugung rauscharmer, lichtstarker Phasenhologramme", *Optik*, **34**, 240-53, (1971)
- 13 A. Graube, "Advances in Bleaching Methods for Photographically Recorded Holograms", *Appl. Opt.*, **13**, 2942-46, (1974)
- 14 M. J. Landry, G. D. Phipps and C. E. Robertson, "Measurement of diffraction efficiency, SNR, and resolution of single- and multiple-exposure amplitude and bleached holograms", *Appl. Optics*, **17**, 1764-70, (1978)
- 15 R. L. van Renesse and F. A. J. Bouts, "Efficiency of Bleaching Agents for Holography", *Optik*, **38**, 156-68, (1973)
- 16 A. A. Ward and L. Solymar, "Diffraction efficiency limitations of holograms recorded in silver-halide emulsions", *Applied Optics*, **28**, 1850-55, (1989)
- 17 S. Sjolinder, "Dichromated Gelatin and the Mechanism of Hologram Formation", *Photographic Science and Engineering*, **25**, 112-118, (1981)
- 18 I. Bányász, "Method for the evaluation of the effects of film nonlinearities on the holographic image", *Optics Letters*, **18**, 658-660, (1993)
- 19 I. Bányász, A. Fimia, A. Beléndez and L. Carretero, "Nonlinear recording of amplitude holograms in agfa 8E75HD: comparison of two developers", *Optics Communications*, **111**, 225-232, (1994)
- 20 A. E. S. Green and R. D. McPeters, "New Analytic Expressions of Photographic Characteristic Curves", *Appl. Opt.* **14**, 271-72, (1975)
- 21 H. Kasprzak, N. Sultanova and H. Podbielska, "Nonlinear effects of the recording material on the image quality of a Fourier hologram", *JOSA A*, **4**, 843-46, (1987)