ELSEVIER
1 October 1994
Optics Communications 111 (1994) 225–232
OPTICS COMMUNICATIONS

Nonlinear recording of amplitude holograms in agfa 8E75HD: comparison of two developers

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Received 8 June 1994

Abstract

Nonlinear holographic characteristics of Agfa 8E75HD plates processed with two developers were measured. To assess the effects of nonlinear recording, reconstructed holographic images of a microline test object were numerically calculated by using these characteristics. The possibility of optimizing the recording parameters was demonstrated.

1. Introduction

Nonlinear characteristics of holographic recording materials have been studied since the 1960's. A number of papers appeared on the effects of nonlinear recording on the quality of the holographic image. The greatest part of them was based on the use of the amplitude transmittance (t) versus exposure (E) curve of the recording material [1–8]. However, the t–E curve is strictly applicable only to thin absorption holograms. The approximate forms of the t–E curve and the interpretation of the higher order terms in the transmittance of the processed hologram posed further restrictions on the validity of these results. It was Lin [9] who first suggested the use of the $\sigma(E_0, V)$ function for characterizing the holographic recording materials, where σ is the square root of the diffraction efficiency of a hologram recorded with two plane waves with a bias exposure of E_0 and a visibility of the interference fringes of V. This function is applicable to the description of all kinds of holograms.

Although $\sigma(E_0, V)$ curves of silver halide and other holographic recording materials were often published in the literature, they are not sufficient for the complete description of holographic imaging because the range of either the bias exposures or visibilities covered in the measurements was usually not wide enough. In the first part of this report we present a systematic measurement of the $\sigma(E_0, V)$ and $t(E)$ functions of Agfa 8E75HD processed by two developers to yield absorption holograms. In the second part of the paper these characteristics are used for the evaluation of the reconstructed holographic images of a test object by a method published recently [10].

2. Experiments

We recorded two series of elementary (plane wave) transmission holograms in Agfa-Gevaert 8E75HD

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SSDI 0030-4018(94)00387-4

high resolution holographic plates. The two collimated beams impinged at the hologram symmetrically with an interbeam angle of 37.6°. The holograms were recorded and reconstructed by a helium–neon laser operating at a wavelength of 632.8 nm, hence the spatial frequency of the holographic gratings was 1019 lines/mm. The bias exposure ranged from 1 to 50 μJ/cm², while the beam ratio was between 1 and 113.

The exposed plates were developed with two processes. They are called AAC and Pyrogallol, after the main components of the developers. The developer plays a crucial role in the formation of both absorption and bleached holograms in silver halide materials. The effects of different developers were analyzed for example by Phillips and his co-workers [11–13]. Phillips pointed out that the Pyrogallol developer, first proposed for holography by Van Renesse and Bouts [14], plays a fundamental role in the formation of the high index modulation needed to achieve high efficiency and good signal-to-noise ratio in bleached holograms. Pyrogallol has a very strong tanning effect on the gelatin. AAC is also an excellent chemical developer for holography [15], but with different action.

The processes are summarized in the following:

1.	Develop	AAC/Pyrogallol	4/3 min.
2.	Wash		1 min.
3.	Fix	F-24	5 min.
4.	Wash		10 min.

Temperature: 20 C°

The compositions of the two developers are:

AAC:	Ascorbic Acid	18 g
	Sodium Carbonate	120 g
	Water to make	1 litre
Pyrogallol:	Ascorbic Acid	18 g
	Pyrogallol	10 g
	Sodium Carbonate	120 g
	Water to make	1 litre

We measured transmission and diffraction efficiency of the holograms as a function of bias exposure and fringe visibility. The diffraction efficiency was defined as the ratio between the power in the first diffracted order and that of the incident beam, corrected for the reflection losses at the surfaces of the plates.

The t–E curves (also corrected for reflection losses) obtained by the two developers are shown in Figs. 1 and 2. The symbols represent measured data and the lines analytical functions fitted to the experimental values. They are of the following form:

$$t(E)=\frac{c}{(E/E_0)^{\kappa}+1}, \tag{1}$$

where c, E_0 and κ are parameters describing the $t(E)$ function.

It can be seen that Pyrogallol produces a steeper $t(E)$ curve with a shorter quasi-linear range than AAC.

Square root of the measured diffraction efficiencies is presented by the symbols in Figs. 3 and 4. The maximum diffraction efficiency obtained by the two developers is about the same, while the holographic

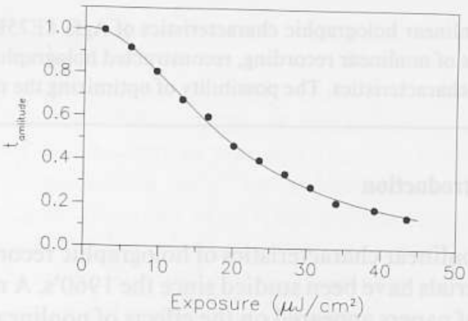

Fig. 1. Amplitude transmission of Agfa 8E75HD versus exposure. AAC developer. Points: measured data. Solid line: fitted by Eq. (1), $c=1.008$, $E_0=18.869$ μJ/cm², $\kappa=2.058$.

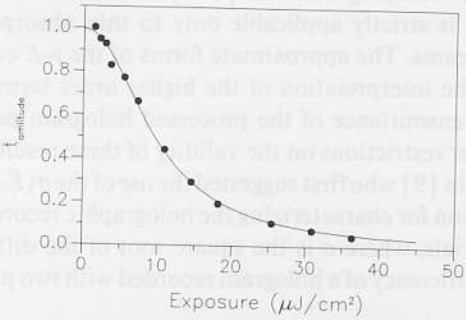

Fig. 2. Amplitude transmission of Agfa 8E75HD versus exposure. Pyrogallol developer. Points: measured data. Solid line: fitted by Eq. (1), $c=0.997$, $E_0=9.751$ μJ/cm², $\kappa=2.114$.

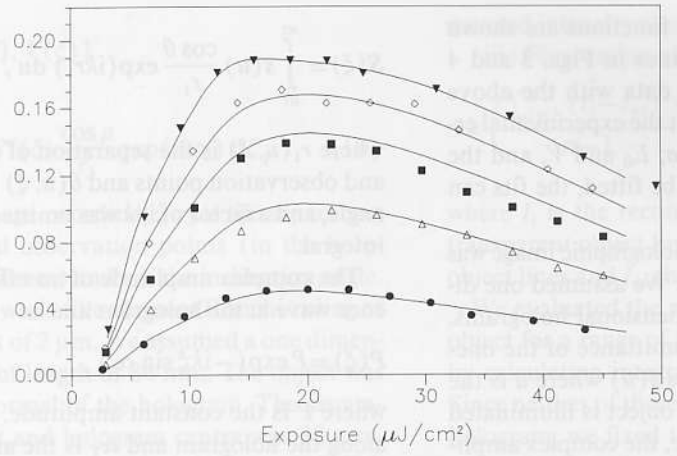

Fig. 3. $\sigma(E_0, V)$ function of Agfa 8E75HD. Developer: AAC. Symbols: experimental data. Lines: fitted by Eq. (2) with parameters shown in Table 1.

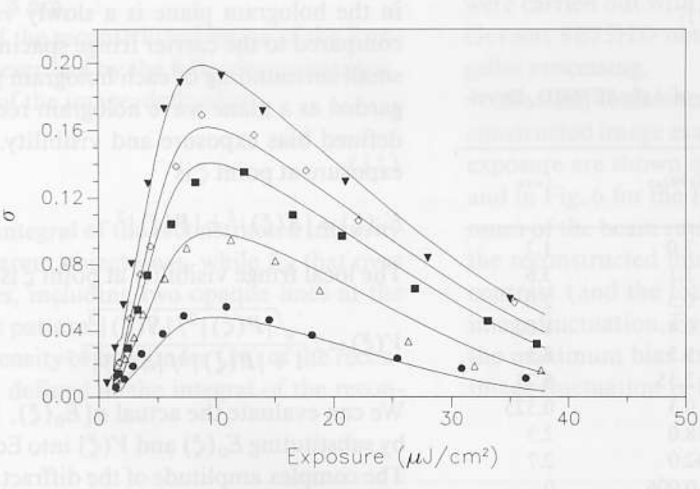

Fig. 4. $\sigma(E_0, V)$ function of Agfa 8E75HD. Developer: Pyrogallol. Symbols: experimental data. Lines: fitted by Eq. (1) with parameters shown in Table 2.

sensitivity of the pyrogallol processing is about twice as great as that of the AAC processing.

3. Theory

We fitted the following analytical function to the measured $\sigma(E_0, V)$ curves [10]:

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

where 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:

$$\mathrm{Par}(E_0) = c_{i01}\left(\frac{1}{[(c_{i11}-E_0)/\exp c_{i12}]+1} + c_{i13}\right) \times\left(\frac{1}{[(E_0-c_{i21})/\exp c_{i22}]+1} + c_{i23}\right) \times\left(\frac{1}{[(c_{i31}-E_0)/\exp c_{i32}]+1} + c_{i33}\right), \tag{3}$$

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

The parameters of the fitted functions are shown in Tables 1 and 2. The solid lines in Figs. 3 and 4 represent fits to the measured data with the above function. If we take into account the experimental errors affecting the precision of σ, E_0 and V, and the great number of parameters to be fitted, the fits can be regarded to be satisfactory.

The reconstructed nonlinear holographic image was evaluated in the following way. We assumed one dimensional objects and one dimensional holograms. If the complex amplitude transmittance of the one-dimensional amplitude object is $s(u)$ where u is the local object coordinate and the object is illuminated perpendicularly by a plane wave, the complex amplitude distribution of the object wave in the hologram line can be described by the following form of the Fresnel–Kirchhoff integral [16]:

Table 1
Parameters of the $\sigma(E_0, V)$ function of Agfa 8E75HD. Developer: AAC

Indices (xx)	c_{fxx}	$c_{(V0)xx}$	c_{wxx}
01	0.43	3.0	1.7
11	6.05	3.1	3.6
12	5.3	0.5	2.0
13	0	0.4	1.02
21	43.0	9.5	8.1
22	17.0	2.35	3.25
23	0	0.3	0.325
31	3.65	18.0	2.3
32	0.65	42.0	2.7
33	0	0.006	0

Table 2
Parameters of the $\sigma(E_0, V)$ function of Agfa 8E75HD. Developer: Pyrogallol

Indices (xx)	c_{fxx}	$c_{(V0)xx}$	c_{wxx}
01	0.43	7.0	5.3
11	3.1	1.8	1.9
12	1.7	0.145	0.16
13	0	0.35	0.35
21	21.5	2.4	4.2
22	11.2	2.35	12.5
23	0	0.125	0.17
31	1.5	8.0	10.0
32	0.25	40	30
33	0	0.09	0.09

$$S(\xi)=\int_{u_1}^{u_2} s(u)\,\frac{\cos\theta}{r_1}\exp(ikr_1)\,du\,, \tag{4}$$

where $r_1(u,\xi)$ is the separation of the actual source and observation points and $\theta(u,\xi)$ is the inclination angle, and a factor of i/λ was omitted from before the integral.

The complex amplitude of an off-axis plane reference wave at the hologram line is

$$P(\xi)=P\exp(-ik\xi\sin\alpha_r)\,, \tag{5}$$

where P is the constant amplitude, ξ the coordinate along the hologram and α_T is the angle of incidence of the reference wave.

In case the intensity distribution of the object wave in the hologram plane is a slowly varying function compared to the carrier fringe spacing, a sufficiently small surrounding of each hologram point can be regarded as a plane wave hologram recorded at a well defined bias exposure and visibility. The local bias exposure at point ξ is

$$E_0(\xi)=|S(\xi)|^2+|P(\xi)|^2 \tag{6}$$

The local fringe visibility at point ξ is

$$V(\xi)=2\,\frac{\sqrt{|P(\xi)|^2/|S(\xi)|^2}}{1+|P(\xi)|^2/|S(\xi)|^2}\,. \tag{7}$$

We can evaluate the actual $\sigma[E_0(\xi), V(\xi)]$ function by substituting $E_0(\xi)$ and $V(\xi)$ into Eqs. (2) and (3). The complex amplitude of the diffraction limited first order real image at the hologram line is

$$H(\xi)=M(\xi)P(\xi)S^*(\xi)\,, \tag{8}$$

where * stands for the complex conjugation and in case of perfect reconstruction the complex amplitude of the reconstruction wave is the complex conjugate to that of the reference wave:

$$M(\xi)=P(\xi)^*\,. \tag{9}$$

In case the different diffraction orders do not overlap in the image space the complex amplitude, $h(x)$ of the reconstructed nonlinear first order real image is readily obtained by multiplying the diffraction limited complex amplitude (8) by the $\sigma[E_0(\xi), V(\xi)]$ function, and performing the second Fresnel-Kirchhoff integration:

$$h(x) = \int_{\xi_1}^{\xi_2} \sigma[E_0(\xi), V(\xi)]$$

$$\times M(\xi)\, P(\xi)\, S^*(\xi)\, \frac{\cos\rho}{r_2} \exp(ikr_2)\, d\xi\,, \qquad (10)$$

where x is the image coordinate, r_2 is the separation of the source and observation points (in the hologram and image planes) and ρ is the inclination angle.

The test object was a five-element Ronchi-ruling of a grating constant of 2 μm. We assumed a one dimensional hologram of length of 84 mm. The object was centred on the normal of the hologram. The separation of the object and hologram centre was 32 mm. Thus the numeric aperture of the hologram was 0.795. Both the recording and the reconstruction wavelength were 632.8 nm.

The quality of the reconstructed image of the Ronchi ruling was described by the following quantities:

(i) Contrast of the image, defined as

$$C = \frac{I_{tr}}{I_{op}}\,, \qquad (11)$$

where I_{tr} is the integral of the reconstructed intensity over the transparent object lines, while I_{op} that over the opaque ones, including two opaque lines at the edges of the test pattern.

(ii) Total intensity or brightness (I_T) of the reconstructed image, defined as the integral of the reconstructed intensity along the whole object.

(iii) Fluctuation of the reconstructed image:

$$\Delta = \left(\frac{\sum_{i=1}^{n} (I_i - I_{av})^2}{n-1} \right)^{1/2}, \qquad (12)$$

where I_i is the reconstructed intensity over the ith transparent object line, n the number of transparent object lines and I_{av} the average of the I_i values.

We evaluated the reconstructed images of the test object for a range of bias exposures and beam ratios by calculating integrals (4) and (10) numerically. Since neither of these quantities is constant along the hologram, we fixed the maximum of the bias exposure (E_0) and the minimum of the beam ratio (R) along the hologram in every case. The calculations were carried out with the characteristics of the Agfa-Gevaert 8E75HD obtained by both AAC and Pyrogallol processing.

Contrast, total intensity and fluctuation of the reconstructed image as a function of the maximum bias exposure are shown in Fig. 5 for the AAC developer and in Fig. 6 for the Pyrogallol developer. The minimum of the beam ratio is fixed, $R=1$. The quality of the reconstructed image is the higher the higher the contrast (and the total intensity) and the lower the image fluctuation. For the case of the AAC developer the maximum bias exposure required for minimum image fluctuation is 12.5 μJ/cm², while for the case

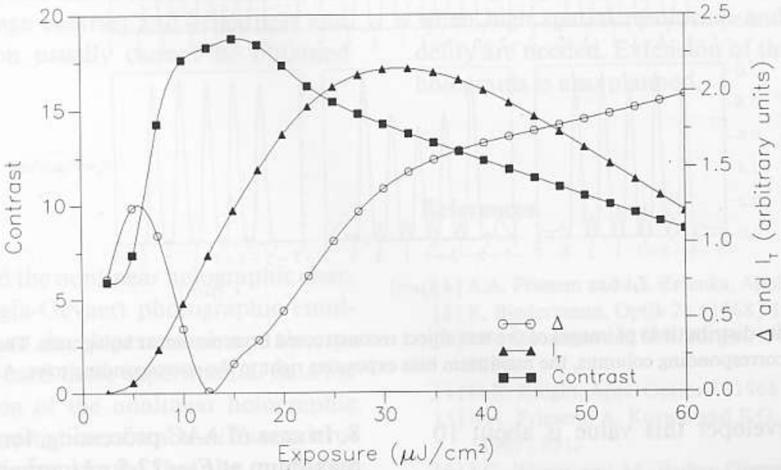

Fig. 5. Calculated contrast, brightness (I_T) and intensity fluctuation (Δ) of the reconstructed holographic image of the test object as a function of the maximum bias exposure. The minimum of the beam ratio is 1. AAC developer.

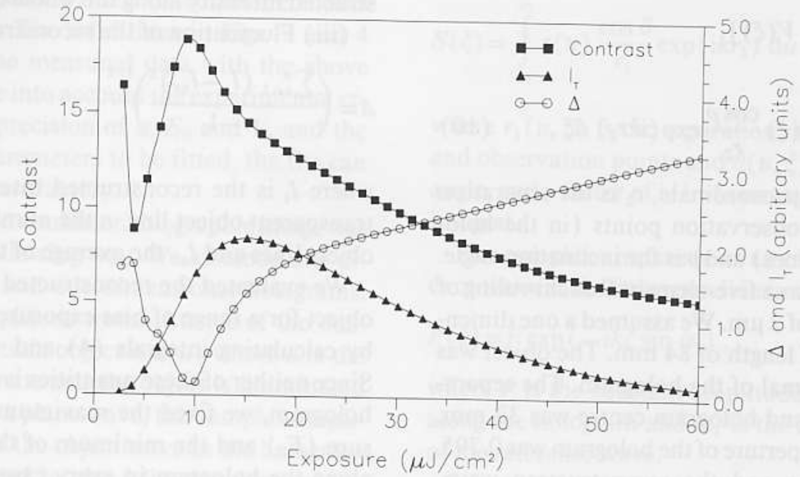

Fig. 6. Calculated contrast, brightness (I_T) and intensity fluctuation (Δ) of the reconstructed holographic image of the test object as a function of the maximum bias exposure. The minimum of the beam ratio is 1. Pyrogallol developer.

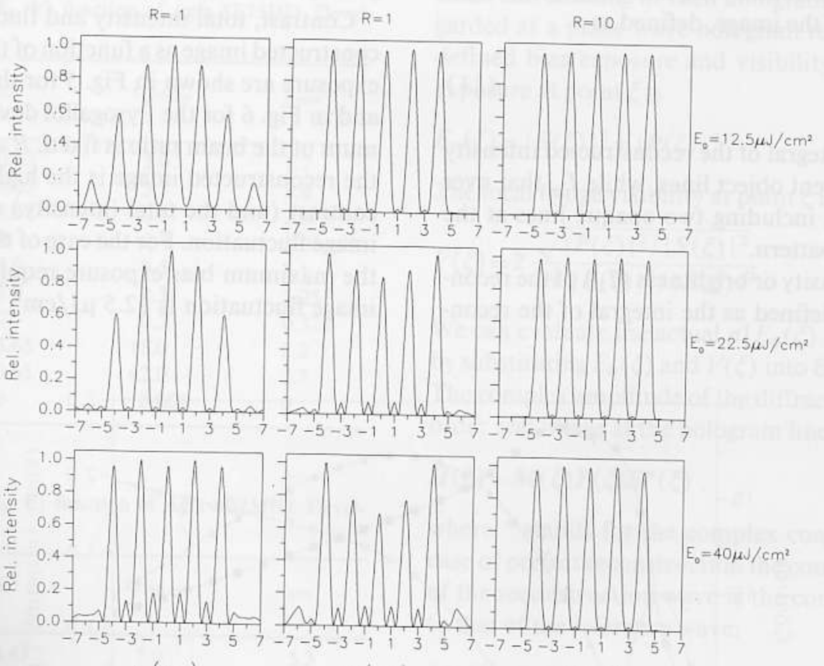

Fig. 7. Calculated intensity distributions of images of the test object reconstructed from nonlinear holograms. The minimum beam ratios are indicated above the corresponding columns, the maximum bias exposures right to the corresponding rows. AAC developer.

of the Pyrogallol developer this value is about 10 μJ/cm^2.

To illustrate the results, we present two series of the reconstructed intensity distributions in Fig. 7 and 8. In case of AAC processing, for $R=0.1$, contrast is maximum at $E_0=22.5$ μJ/cm^2 and Δ is minimum at $E_0=40.0$ μJ/cm^2. For $R=1$, Δ is minimum at $E_0=12.5$ μJ/cm^2. For $R=10$, Δ is minimum and I_T

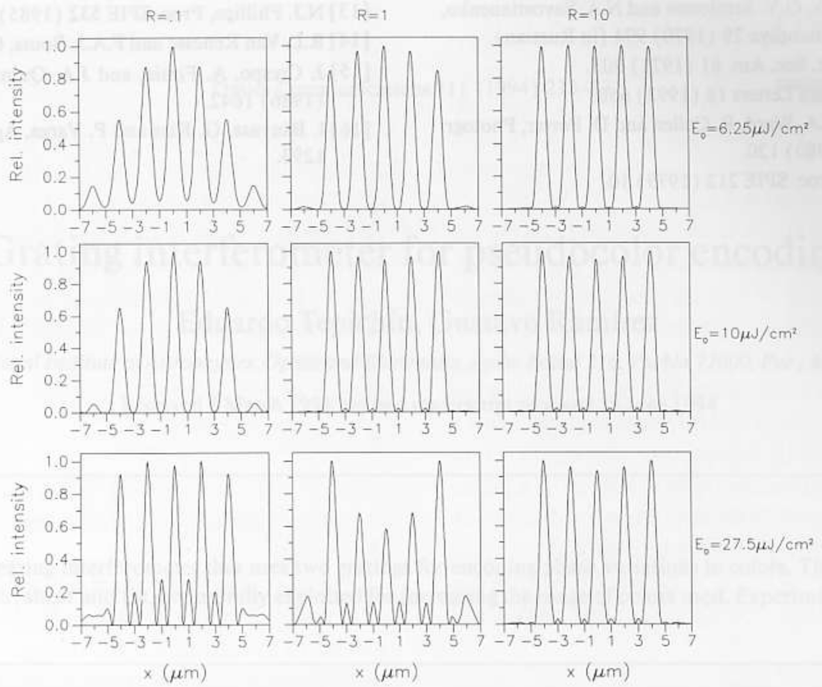

Fig. 8. Calculated intensity distributions of images of the test object reconstructed from nonlinear holograms. The minimum beam ratios are indicated above the corresponding columns, the maximum bias exposures right to the corresponding rows. Pyrogallol developer.

is maximum at $E_0=22.5$ μJ/cm^2. In case of Pyrogallol processing, for $R=0.1$, Δ is minimum at 27.5 μJ/cm^2. For $R=1$, Δ is minimum at $E_0=10$ μJ/cm^2. For $R=10$, Δ is minimum at $E_0=6.25$ μJ/cm^2 and I_T is maximum at $E_0=10.0$ μJ/cm^2.

It can be seen that one has to make a tradeoff, because maximum image contrast and brightness and minimum fluctuation usually cannot be obtained simultaneously.

4. Conclusions

We have measured the nonlinear holographic characteristics of the Agfa-Gevaert photographic emulsion processed by two developers to obtain absorption holograms. We used these experimental data for numerical simulation of the nonlinear holographic recording and reconstruction of a non-diffuse micro-line object. It was demonstrated that the quality of the holographic image (characterized by its contrast, brightness and fluctuation) can be optimized by a suitable choice of the bias exposure and beam ratio at recording. The optimal values of these parameters depend strongly on the processing of the hologram and they are different for different types of objects. We hope that this method can be applied successfully in designing holographic optical elements, especially when high spatial resolution and reconstruction fidelity are needed. Extension of this method to phase holograms is also planned.

References

[1] A.A. Friesem and J.S. Zelenka, Appl. Optics 6 (1967) 1755.
[2] K. Biedermann, Optik 28 (1968) 160.
[3] J.W. Goodman and G.R. Knight, J. Opt. Soc. Am. 58 (1968) 1276.
[4] G.R. Knight, Appl. Optics 7 (1968) 205.
[5] A.A. Friesem, A. Kozma and F.G. Adams, Appl. Optics 6 (1967) 851.
[6] J.C. Wyant and M. Parker Givens, J. Opt. Soc. Am. 59 (1969) 1650.
[7] F.J. Tischer, Appl. Optics 9 (1970) 1369.

[8] Yu. N. Denisyuk, G.V. Semionov and N.A. Savostianenko, Optika i Spectroscopiya 29 (1970) 994 (in Russian).
[9] L.H. Lin, J. Opt. Soc. Am. 61 (1971) 203.
[10] I. Bányász, Optics Letters 18 (1993) 658.
[11] N.J. Phillips, A.A. Ward, R. Cullen and D. Porter, Photogr. Sci. Eng. 24 (1980) 120.
[12] N.J. Phillips, Proc. SPIE 212 (1979) 10.
[13] N.J. Phillips, Proc. SPIE 532 (1985) 29.
[14] R.L. Van Renesse and F.A.J. Bouts, Optik 38 (1973) 156.
[15] J. Crespo, A. Fimia, and J.A. Quintana, Appl. Optics 25 (1986) 1642.
[16] I. Bányász, G. Kiss and P. Varga, Appl. Optics 27 (1988) 1293.

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1 December 1995

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Optics Communications 121 (1995) 166

Erratum

Nonlinear recording of amplitude holograms in Agfa 8E75HD: comparison of two developers (Optics Comm. 111 (1994) 225)

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On p. 227, Eq. (3) appeared incorrectly. Eq. (3) reads correctly as follows:

$$\mathrm{Par}(E_0) = c_{i01}\left(\frac{1}{\exp[(c_{i11}-E_0)/c_{i12}]+1}+c_{i13}\right) \times\left(\frac{1}{\exp[(E_0-c_{i21})/c_{i22}]+1}+c_{i23}\right)\left(\frac{1}{\exp[(c_{i31}-E_0)/c_{i32}]+1}+c_{i33}\right) \tag{3}$$

SSDI 0030-4018(95)00560-9