starting point for a detailed study of the efficiency and the image resolution of holograms. In color holography and other applications utilizing multiple exposures with different sets of beams, often of different wavelength, the reconstruction may be degraded by the presence of spurious images due to the coupling of each reconstructing beam with each independent hologram encoded on the film plate. The degree of suppression of the spurious images can be measured from curves similar to that shown in Fig. 1.

[1] E. N. Leith and J. Upatnieks, *J. Opt. Soc. Am.* **53,** 1377 (1963).
[2] J. M. Burch and D. A. Palmer, *Optica Acta* **8,** 73 (1961).
[3] A. K. Rigler and T. P. Vogl, *Appl. Optics* **5,** 186 (1966).
[4] G. R. Harrison, *J. Opt. Soc. Am.* **39,** 413 (1949).
[5] P. Glafkides, *Photographic Chemistry 1, 2,* Fountain Press, London (1958).
[6] A. A. Frieseim, *Appl. Phys. Letters* **7,** 102 (1965).
[7] C. Kittel, *Introduction to Solid State Physics,* Wiley, New York (1959).
[8] E. N. Leith, *Electronics* **39,** 88 (1966).
[9] W. T. Cathy, Jr., *J. Opt. Soc. Am.* **55,** 457 (1965).

WHITE-LIGHT RECONSTRUCTION OF COLOR IMAGES FROM BLACK-AND-WHITE VOLUME HOLOGRAMS RECORDED ON SHEET FILM

George W. Stroke and Richard G. Zech
The University of Michigan
Ann Arbor, Michigan

(Received 8 August 1966)

The method of "white-light reflection holography" first described by Stroke and Labeyrie (Physics Letters *20,* 368, March 1, 1966) and subsequently verified by a number of authors, has now been extended to the recording of volume holograms in 6–7-μ-thick Kodak 649F emulsions on sheet film, with a quality in the reconstructed images comparing favorably with the images reconstructed from the 17-μ-thick emulsions on glass plates used heretofore. The results presented have also permitted us to further verify a simple "crystallographic" theory of the method, first used by Stroke and Labeyrie (*ibid.*) and further described by G. W. Stroke in a subsequent paper.

A great interest appears to have recently arisen in a method of "white-light color reflection holography" first described by Stroke and Labeyrie.[1] The method has now been verified by a number of authors[2–4] and permits one to reconstruct single-color and multicolor images upon illumination of black-and-white holograms with a source of ordinary white light, such as a flashlight, a zirconium arc, or the sun. "Volume holography" work[1–6] appears heretofore to have been carried out only on comparatively "thick" emulsions (on the order of 17 μ for the Kodak 649F emulsions used) coated on glass-plate support.

The "crystal-like" nature of the volume holograms, with "planes" parallel to the surface of the emulsions, as it appears in white-light holography applications was stressed by Stroke and Labeyrie.[1] It is clear that a sufficiently great number of "crystal-like planes" must be available throughout the thickness of the emulsion to give the hologram the desired crystal-like characteristics. It appeared therefore to be of a particular interest, also in view possibly of a wider and more ready use of this type of hologram (for instance to display molecular models in crystallography), to determine whether (if necessary) the white-light reflection volume holograms could be recorded in comparatively much thinner emulsions (on the order of 6 to 7 μ, the thickest available for the Kodak 649F sheet film used) than those used heretofore, and especially whether good wavefront and image reconstructions could be obtained from a comparatively flexible sheet film, such as that which we have used in this work.

Figure 1 shows one of the arrangements which we have been using to record white-light reflection holograms on 4″ × 5″ film. The film was exposed with the reference beam incident onto the emulsion through the anti-halation backing (used in the production of this film), and a suitable adjustment was made in the beam intensities, so that the reference beam and the beam scattered by the object both had the *same* intensity, as measured in polarized light in the emulsion plane. (The transmission of the anti-halation backing of this film in 6328 Å in polarized light is approximately 13.3%). During the recording the film is seen to have been placed between two "micro-flat" glass plates (obtained by removing the emulsion from photographic plates used in previous work).

Figure 2 shows a photograph of the image reconstructed from the hologram recorded in the arrangement of Fig. 1. The reconstructed image was obtained by illuminating the sheet-film hologram with a 300-W zirconium arc, placed at a distance of about 20 in. from the hologram (that is, at the distance of the point source producing the reference beam in the recording). Significantly it is seen that good images can be reconstructed from sheet film flattened down only on a piece of cardboard with no more than some "Scotch" tape.

It may be of interest to recall that the "white-light" reconstruction of images from black-and-white reflection holograms is based on recording a crystal-like grating throughout the volume of the holographic emulsion.[1] The intensity distribution of the holograms, $I(x, y, z)$, throughout the volume of the emulsion consists of a record (obtained in monochromatic light) of the standing-wave pattern formed by interference between the traveling waves $\mathbf{E}_0(x, y, z, t)$ scattered by the object, on the one hand, and the traveling "reference" wave (e.g., spherical or plane) $\mathbf{E}_R(x, y, z, t)$, on the other. The two waves $\mathbf{E}_0$ and $\mathbf{E}_R$ are made to be incident onto the photographic emulsion from *opposite* sides of the emulsion (and generally with a direction nearly normal to the surfaces of the emulsion). In the reconstruction, illumination of the hologram from the reference beam side with waves now originating from a source of "white light" (e.g., flash light, zirconium arc, sun, etc.), but with the waves having a *geometrical* shape equal to (or very similar to) the shape of the reference wave $\mathbf{E}_R$ (used in the recording) results in the diffraction of single-color waves $\mathbf{E}_0$ (x, y, z, t), quite in analogy with the behavior of a crystal when diffracting x rays under analogous circumstances.[1] (Multicolor reconstructions with white-light illumination are obtained simply by superposing the intensity components $I(x, y, z)_\lambda$ corresponding to the number of desired color components in the waves scattered by the object).[2,6] Because of the analogy of white-light reflection holograms with "x-ray" crystals,[1] and because the theory of crystallographic diffraction is well developed (see e.g., ref. 7) we have already previously stressed[1] that no special theory appears to be required to interpret the basic properties of these holograms, nor indeed to even qualitatively describe the white-light reconstruction, provided that one recognizes the intensity distribution $I(x, y, z)$ throughout the volume of the emulsion as corresponding to the electron-density distribution $\rho(x, y, z)$ in the case of crystals.[8]

In analogy with x-ray crystallography, the single-color waves (or component waves) scattered by the hologram upon white-light illumination will be dif-

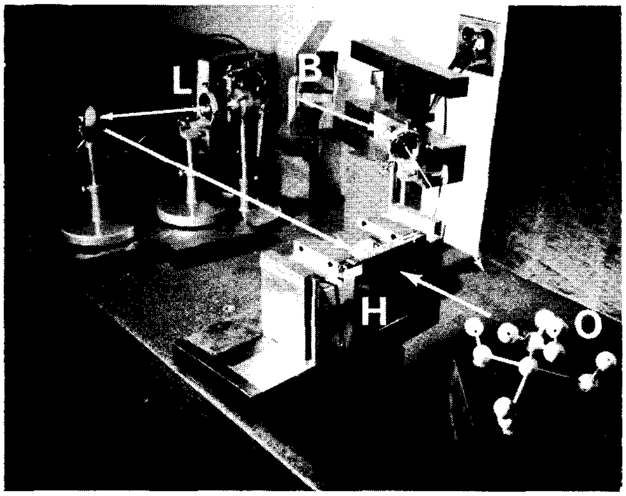

Fig. 1. Holographic arrangement used for the recording of "white-light reflection holograms" on sheet film. L, He-Ne laser; B, beam-splitting mirror; O, object; H, hologram. The arrows indicate the light paths, showing notably that the reference beam and the beam scattered by the object are incident onto the hologram from *opposite* sides of the emulsion according to ref. 1 with the E vectors of the beams normal to the plane formed by the propagation vectors of these beams (i.e. normal to the plane of the granite table in this figure).

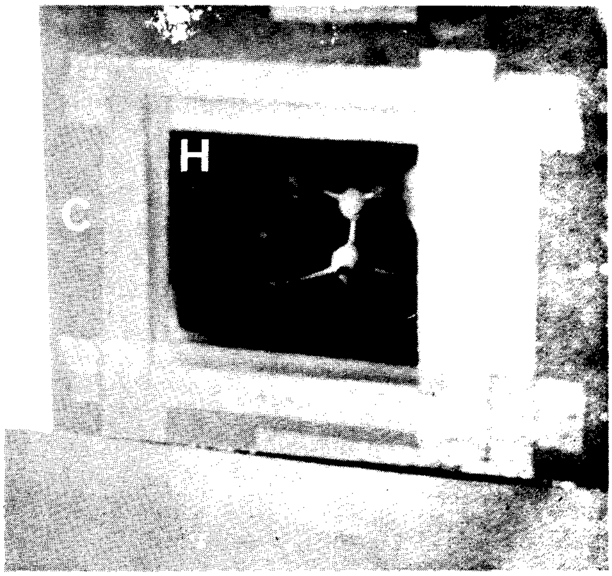

Fig. 2. Photograph of image reconstructed by illuminating the sheet-film hologram (recorded in the arrangement of Fig. 1) by a "white-light" zirconium arc (see text). H, hologram; C, supporting cardboard. Except for the use of sheet film, the method used is identical to the method of "white-light reconstruction of holographic images using the Lippmann-Bragg diffraction effect" first described by Stroke and Labeyrie in ref. 1.

fracted according to Bragg's law ($2 \sin i = \lambda/d$) so that the illuminating and reconstructed waves (of a particular wavelength λ) form equal angles i with the "planes" of which the mean distance is d. (For the case of the multicolor holograms, the ratio λ/d happens to remain the same in the recording so that all the component waves, of different wavelengths, will be diffracted in the *same* direction upon white-light illumination from a given angle i in the reconstruction).[1,2]

We may recall in conclusion that certain analogies of the interferometric recording of *wavefronts* (as in holography), and the interferometric recording of color *images* (as in Lippmann photography[9]) were first stressed by Denisyuk[10] in 1962, with a particular emphasis on the recording of optical wavefronts throughout the volume of the emulsion as an extension of the work of Dennis Gabor[11] first given in 1948. Subsequently, and apparently quite independently, Van Heerden[12] discussed a theory of optical information storage in solids by interferometric means, analogous to the holographic principles first given by Gabor. In a general way, it appears increasingly, as we have stressed many times before (see, for example, and also for general background, ref. 13), that all the methods of holography are indeed based on the work by Gabor.

We acknowledge the generous grant made by the National Science Foundation in support of this work. One of us (GWS) also wishes to acknowledge a number of fruitful conversations and private communications from a number of colleagues and students, notably from Prof. Dennis Gabor regarding the theory of white-light reflection holograms, from Professors W. F. Berg, E. Klein, and H. Nassenstein regarding photographic properties of emulsions suitable for the recording of holograms, and from Dr. Edwin H. Land regarding, among many other fruitful suggestions, clarifications of the interpretation of our work on multicolor holography (ref. 2.) in terms of his theory and work on "two-color" photography. GWS also wishes to acknowledge the private communication from Dr. Glen T. Sincerbox who first drew his attention to the work of Denisyuk (after a colloquium on holography given by GWS at the IBM Thomas J. Watson Research Center in Yorktown Heights, N. Y. on 18 February 1965). Finally, GWS also wishes to thank Prof. John C. Kendrew and Dr. Herman Watson, for their fruitful comments and encouragement.

1 G. W. Stroke and A. Labeyrie, *Phys. Letters* **20**, 368 (1966).

2 L. H. Lin, K. S. Pennington, G. W. Stroke, and A. Labeyrie, *Bell System Tech. J.* **45**, 659 (1966).

3 J. Upatnieks, J. Marks, and R. Fedorowicz, *Appl. Phys. Letters* **8**, 286 (1966).

4 E. N. Leith, A. Kozma, J. Upatnieks, J. Marks, and N. Massey, *Appl. Optics* **5**, 1303 (1966).

5 K. S. Pennington and L. H. Lin, *Appl. Phys. Letters* **7**, 56 (1965).

6 R. J. Collier, *IEEE Spectrum* **3**, 67 (1966).

7 A. Guinier, *X-Ray Diffraction* (W. H. Freeman and Co., San Francisco and London, 1963).

8 G. W. Stroke, paper presented on 26 May 1966 at the Swiss Federal Institute of Technology, Zurich, upon invitation from Prof. W. F. Berg, director of the Institute for Photography, ETH.

9 G. Lippmann, *J. de Physique* **3**, 97 (1966).

10 Yu. N. Denisyuk, *Soviet Phys.—Doklady* **7**, 543 (1962); *Opt. and Spectr.* (English transl.) **15**, 279 (1963); *ibid.*, **18**, 152 (1965).

11 D. Gabor, *Nature* **161**, 777 (1948).

12 P. J. Van Heerden, *Appl. Optics* **2**, 387 (1963); *ibid.*, **2**, 393 (1963).

13 G. W. Stroke, *An Introduction to Coherent Optics and Holography* (Academic Press, New York and London, 1966) [270 pages, including the reprints of the three "wavefront-reconstruction" imaging papers by D. Gabor].

ERRATA

In "A Zone-Plate Aperture for Enhancing Resolution in Phase-Contrast Electron Microscopy," [*Appl. Phys. Letters* **8**, 258 (1966)], C. B. Eisenhandler and B. M. Siegel, Dept. of Engineering Physics and Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York, the following equations were incorrectly printed and should read:

Eq. (2): $$\mathrm{Re}\ [\psi(r^i)] = 2\pi(1-\beta^2)^{-1/2}\,(M\lambda)^{-1} \int_{\text{aperture}} f^0[\sin(\alpha/2)/\lambda] \cdot \cos\chi(\alpha) J_0(2\pi\alpha r^i/\lambda)\alpha d\alpha$$

Eq. (4): $$\chi_{\max} = \pi(1/2 + \Delta f^2/2C_s\lambda) = 1.21\pi$$

Eq. (7): $$\chi_{\max} = \pi(1/2 + \Delta f^2/2C_s\lambda) = (K+0.21)\pi \qquad K = 1, 3, 5\ldots$$

Eq. (9): $$\alpha_n = \{\Delta f/C_s - [\Delta f^2/C_s^2 - (n-1)\lambda/C_s]^{1/2}\}^{1/2}$$

for $n = 1, 5, 9 \cdots 2K-1$ (transparent);
for $n = 3, 7, 11 \cdots 2K-3$ (opaque).