Handbook of Optical Holography

H. J. CAULFIELD

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Preface

Holography is in its third historical cycle. The first, in the late 1940s, derived from Gabor's first papers in *Nature*. The field attracted brilliant researchers (Lohmann, Rogers, etc.) but little general interest. The second, in the mid 1960s, derived from the Leith and Upatnieks papers in the *Journal of the Optical Society of America* and from the almost simultaneous availability of continuous wave visible lasers. That time the enthusiasm of holography's proponents was so great that the reality appeared to fall far short of the promise. Major holography efforts were started but soon dissolved. Many "holographers" were forced into other fields. Government support dried up. The third and present phase has no clear birthdate and no clear seminal paper. It began in the mid 1970s with a slow but steady rebirth of interest and support. This is a phase in which enthusiasm is great but is tempered by realism. In the midst of this phase, a number of us who have worked in holography for many years thought it wise to gather together what we knew so far, in the hope that such a "handbook" would help the field we enjoy and love to progress in a rapid and orderly way.

This, then, is a book with a mission. The success of that mission requires that readers not seek the wrong things from this book. It is not intended as either a self-study book or a college textbook (although it might supplement other books for those purposes). This is a book for people who want to use holography—whether for industry, government, health services, education, or research. Here you can go to answer such questions as

Is holography of any potential value in solving my particular technical problem?

How good is a holographic lens?

What is the formula for vibrational sensitivity for the kind of hologram I am making?

How do I choose components for my holography setup?

What is this undefined jargon in the technical paper I am reading?

What recording medium should I use?

It is not intended that this book be read through as one might read a novel or even a textbook. Rather, it should be the book to which the reader turns when he has a specific question.

The list of potential users includes research workers and students, teachers, application engineers, government technical administrators, contract monitors, and policy makers, and users of holographic equipment.

Deliberately omitted to keep the size of the book within reasonable bounds are many important areas of nonoptical holography such as acoustic, microwave, γ- and x-ray, electron, and computer holography.

I have enjoyed editing this book, or at least it seems so now that the inevitable browbeating and clerical problems are behind me. The authors took their assignments seriously and deserve much credit for their good manuscripts. Beyond thanking them, I want to thank some patient employers, J. S. Draper and E. R. Schildkraut, a marvelous secretary, Shirley Fedukowski, and the editorial staff of Academic Press.

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1

Introduction

E. N. Leith

The basic process of photography consists of forming an image of an object (either two or three dimensional) and projecting this image onto a light sensitive surface. Each object point is converted into a corresponding image point, and one is concerned only with the brightness, or irradiance, distribution of the image.

Holography, although also a photographic process, is radically different in concept. Here, the goal is not to record merely the irradiance distribution of an image, but in effect to record the complete wave field as it intercepts the recording plane, which in general is not even an image plane. Recording of the complete wave field means recording the phase as well as the amplitude. The problem lies of course in recording phase. The amplitude (or its square, the irradiance) is easily recorded; any photographic recording material can do that. All detectors are totally insensitive to the phase differences among the various parts of the field. Yet, information about the object is carried in the phase structure, as well as in the amplitude structure, of the field, and both must be sensed if the wave field is to be wholly recorded.

Gabor (1948, 1949, 1951), in his invention of holography, solved the basic problem by means of a background wave, which converts phase differences into intensity differences; thus, phase becomes encoded into a quantity that photographic film can recognize. To this record Gabor applied the name *hologram*, meaning whole record. The pattern of the wave is in effect imprinted into the hologram in such a way that at any desired later time the wave field can be exactly regenerated simply by illuminating the hologram with an appropriate beam of light. This beam, upon passing through the hologram, acquires the phase and amplitude modulation characteristics of the original wave field. It is as though the original wave were captured by the plate and later released. The reconstructed wave then propagates as if it had never been

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interrupted. An observer in the path of the beam will find it indistinguishable from the original wave. He will seem to see the original object, just as he would have seen it if it were still there. He will see it with all the optical properties one expects from viewing the real world; there will be full three dimensionality and all the normal parallax relations of real life. This striking realism is certainly what has made holography a subject of enormous fascination for scientist and laymen alike. Indeed, holography is a most radical departure from conventional photography.

Holography had an important precursor in the Bragg x-ray microscope (Bragg, 1929, 1939, 1942) and in the even earlier work of Wolfke (1920). Bragg, too, had been concerned with obtaining a complete record of the scattered wave field from an object, in his case, a crystal illuminated with x rays. Like holography, Bragg's method was a two-step diffraction process. The scattered x rays from the crystal were photographically recorded, then used to create an analogous field with visible light. In Bragg's case (as well as in Wolfke's) the crystal was a three-dimensional periodic structure, hence under plane wave illumination, only one diffracted wave component (spatial frequency) was produced at a time, in accordance with the rules of Bragg diffraction. This difference is not fundamental to the theory. In any event, one must record the phase and the amplitude, and of course detectors record only the amplitude. Bragg's method was to choose a particular kind of crystal with a symmetry such that the far field diffraction pattern (Fourier transform) of the object distribution is purely real, having no phase. Further, the crystals under consideration were those with a heavy atom at the center, thus providing a bias background which made the Fourier transform positive, as well as real. Thus it sufficed to measure only the magnitudes of the plane waves representing the Fourier components. Bragg, after recording the wave amplitude, would construct a mask consisting of openings whose positions and size represented the values of the Fourier components. The mask, when illuminated with coherent light, would form a far field diffraction pattern that was an image of the atomic structure of the crystal. This work was extended by Buerger (1950), and Boersch (1967) carried out similar experiments in Germany.

This work had been in part anticipated in 1920 by Wolfke, whose work in the meantime had been forgotten. Wolfke also considered the possibility of using the recorded x-ray diffraction pattern from a crystal to obtain an optical image of the crystal lattice and then illuminating the diffraction pattern transparency with a beam of monochromatic light to produce the lattice image, noting that the object must be symmetrical and "without a phase structure."

Gabor's process of holography was suggested by the Bragg microscope. His aim was to improve the image quality of the electron microscope, which suffered from spherical aberration that could not be corrected to the high degree that optical lenses are aberration corrected. The electron lenses are magnetic fields, and their properties cannot be controlled with the precision that can be achieved with optical lenses. Gabor's solution was ingenious and a sharp departure from traditional electron microscopy. He would record the scattered field of the illuminated object, then regenerate the field with optical waves. The spherical aberration would carry over to the optical domain, where it could be corrected by the well known techniques of the lens designer. Prior to undertaking the electron microscope project, he demonstrated the feasibility of the technique, using optical waves for both the making and the reconstruction processes.

Aside from the wavelengths involved (and the use of electron waves instead of electromagnetics), Gabor's proposed method differed from Bragg's in a number of ways. Gabor's process did not produce Bragg diffraction, and the entire field was available at one instant for recording. Also, Gabor's process dealt with Fresnel rather than Fraunhofer diffraction; this distinction is not fundamental, but it did facilitate carrying out the process. The principal distinction is that Gabor's process did not depend on a special class of objects that produced a positive real Fourier transform. Gabor's method required a coherent background wave, analogous to the strong scattering center of the Bragg method, but he was able to produce his coherent background as he wished. In this method, a transparency $s_0 + s$ is illuminated with a coherent light beam, where s_0 is the uniform part of the transparency (the portion of zero spatial frequency) and s is the nonzero spatial frequency part. The Fresnel diffraction pattern can be written

$$u_0 + u, \quad \text{where} \quad s_0 = u_0$$

(i.e., the coherent background is unaltered by the diffraction process), and the irradiance is

$$|u_0 + u|^2 = |u_0|^2 + |u|^2 + u_0u^* + u_0^* u;$$

this is the basic equation of the Gabor technique. If this irradiance distribution is recorded and the record illuminated with a coherent beam, a portion of the resulting field will represent the term u_0^*u, which is a regeneration of the nonzero spatial frequency part of the nondiffracted field. Combining this with the background term $|u_0|^2$ produces a wave which seems to emanate from a virtual object $s_0 + s$ located at the position of the original object.

The process lends itself to two basic interpretations, depending on whether or not we choose to regard s_0 as a part of the object. If s_0 is part of the object, then a photographic recording of the object field results in a complete loss of phase of the object field. But by choosing the object so that the uniform part predominates, the phase of the diffraction pattern is nearly constant, and the loss of the phase is relatively unimportant. This view stresses the similarity to the Bragg process, where because of symmetry and the strong background scatterer, there is no phase to be lost, and the reconstruction can be exact. With the strong background but without the symmetry, as in Gabor's case, this loss of phase, although not catastrophic, does lead to the difficulty of the twin image term u_0u^*.

By an alternative view we think of the object as being only the portion s, with the uniform part being added so as to produce a strong background wave. Again, recording the intensity results in a loss of phase of the total wave $u_0 + u$, but the phase of the signal part u is preserved, although imperfectly, because of the presence of the other term u_0^*u.

Following Gabor's invention of holography, many researchers began working in this new area. Haine, Dyson, and Mulvey continued the effort to make successful holograms with the electron microscope (Haine and Dyson, 1950; Haine and Mulvey, 1952). As with Gabor, the results were less than had been desired. Numerous practical difficulties barred success, including object instability and voltage instabilities in the electron lens power supply. Others pursued purely optical holography, including Rogers (1952), El-Sum and Kirkpatrick (1952), El-Sum (1952), Baez (1952), and Lohmann (1956). The imaging obtained with holography, however, was poor, and interest in this technique subsided until by the 1950s there was little remaining activity in this once promising area. The primary reason for the poor imagery was the twin image. There were other difficulties; the term $| u |^2$ (i.e., self-interference among the scattered waves from the various object points), extraneous terms due to the inevitable nonlinearities of the recording process, and the scattered light from various scattering centers, such as dust and scratches on the various optical elements, all produced noise which overlay the reconstructed image, giving a displeasing appearance. The scatterer noise is not a defect of holography per se but is intrinsic to the coherent light used for holography. Any scatterer in the system produces a wake of scattered light which propagates downstream with the background beam, interfering with it, and producing extraneous patterns that are recorded on the hologram and ultimately overlie the final image.

It has been said that the lack of a bright coherent source (e.g., the laser) caused the early failure of holography. We doubt that this is the case; our own experience in holography and coherent optical processing during our prelaser period, 1955–1962, in general indicated that the brightness and coherence levels obtainable with the mercury arc source were adequate for a wide range of applications, not only for laboratory experiments but even for operational equipment. In short, we had quite phenomenal success.

It was during the ebb of holography that our work, which led to the revival of holography, began. This revival process was a complicated one, with some rather unusual aspects; in particular, it was not just one wave, but several, with each reaching successively further.

The first, which is perhaps best regarded as a precursor, resulted in a minirevival of holography. In 1955, while working in the area of radar, we rediscovered Gabor's process of holography. Our theory was that if radar returns were recorded on photographic film, or a similar optical transparency, and then illuminated with a beam of coherent light, the resulting diffracted light waves could be replicas in miniature of the original radar waves that impinged on the receiving aperture of the radar system. The theory, as it was originally developed, considered both the cases of conventional, real antenna systems and the synthetic aperture system. From the standpoint of holography, it is of course unimportant whether the sample wavefronts are recorded simultaneously (the real aperture) or sequentially (the synthetic aperture). We developed an extensive theory of holography that in many ways paralleled Gabor's original work, which at that time was not known to us.

Despite the prior work of Gabor, our work had some original aspects. First, it introduced into holography the concept of the carrier frequency (i.e., the off-axis technique), which has so effectively disposed of the twin image problem. Second, it addressed the problem of lateral dispersion, which has to do with the tendency of carrier frequency holograms, because of their gratinglike properties, to spectrally disperse the reconstructed waves, thus leading to greater monochromaticity (i.e., temporal coherence) requirements for the off-axis hologram. It proposed the use of a grating that matches the spatial carrier of the hologram in order to compensate for the lateral chromatic dispersion of the hologram. Third, it proposed the use of a Fresnel zone plate to compensate for the longitudinal chromatic dispersion of the hologram, which results in the image plane forming at a distance proportional to the wavelength. This is, of course, the reason that Gabor's holography process requires monochromatic light for the reconstruction process, with an equivalent reason applying for the monochromaticity requirement in the hologram recording process. Thus, when we also consider that the coherence requirements for recording radar data (or indeed, any electrical data) are inherently identical whether the recording process is done in the in-line or off-axis (carrier) mode, it follows that carrier frequency holography, as originally conceived, had considerably less requirement for monochromaticity than had Gabor's original in-line method. This situation may seem surprising to many since it is often, but incorrectly, assumed that off-axis holography intrinsically has a greater monochromaticity requirement than in-line holography.

Finally, our work in a sense turned Gabor's original work around; instead of going from very short wavelengths to optical wavelengths, we went from long wavelengths to optical wavelengths. The technology for performing this alternative operation was much better in hand. It was easy to make holograms at radar wavelengths; the problems that plagued Gabor in the electron domain were not problems at all in the microwave domain. Furthermore, the basic accomplishments of holography, the preservation of the phase of a wave and the subsequent use of the phase, as well as amplitude, to create either a second wave or an image of the original object distribution, was not at all the problem here; the recording of phase and its recovery on readout, which had been Gabor's goal, had in fact been routine at radio wavelengths for many years.

Indeed the theory of holography we developed was essentially a new way of interpreting old established processes. What had originally been described as an optical computation system was now described in terms of holography. This new method of describing old processes seemed to offer many new insights into the optical processing of synthetic aperture radar data. Although slow in gaining acceptance by the radar community, it eventually became firmly established by about 1960. Thus the first wave of holographic revival was hardly earthshaking, although its ultimate effects were considerable.

It is interesting to note that Rogers (1956, 1957), working at about the same time in New Zealand, also applied holography to radio waves, by recognizing that radio waves scattered from the ionsphere, if photographically recorded, could be treated as holograms.

In 1960 we experimented with optical holography, first of all duplicating Gabor's original experiment. Although the quality of the imagery was at that time hardly impressive by the standards of conventional photography, the results were nevertheless startling, inasmuch as this process seemed to create something (the image) from what appeared to be nothing. There in the optical system was an image, produced by rays of light which could be traced upstream in the optical system, toward the source, but only as far as that unintelligible piece of film called the hologram. It contained no discernible object corresponding to the image, yet the image forming rays ended abruptly there. The process, to one unversed in holography, seemed mysterious and inexplicable. Our reaction to this holographic experiment was one of fascination. How much more fascinating it must have been to Gabor and his colleagues when they observed these same effects for the first time!

Our enthusiasm prompted us to seek means for improving the imagery (Leith and Upatnieks, 1962, 1963, 1964). We reasoned that the twin image was basically an aliasing problem and the solution was to place the holographic signal on a spatial carrier. The mechanism for so doing was to introduce a separate coherent background wave, which we called the reference beam. It was to impinge on the recording plate at some nonzero angle with respect to the object wave. This resulted in the Fresnel diffraction pattern of Gabor's holographic process being overlaid with a fine fringe pattern. The photographic record of this two beam overlay became the carrier frequency, or off-axis, hologram, with its fine-line structure. Such a hologram looked like and behaved like a diffraction grating.

When we illuminated this new type of hologram, we produced, as expected, a zero-order wave which behaved like the reconstructed wave of the traditional Gabor hologram, producing the usual inseparable twin images and containing all of the other defects of the in-line case, including the intermodulation term and terms due to nonlinearities in the hologram recording process.

However, also emanating from the hologram was a pair of side orders not before seen from a hologram. These waves separated from the zero order,