Overview of the Development of Holography

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We present an overview of the development of holography, from Gabor to the present. We describe some of the peculiar and interesting twists in this long development. We look at some of the successes and failures, and at some of the early predictions, including those that came to pass, and those that went awry.

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Early Holography

Dennis Gabor invented holography in 1947, now 50 years ago.[1–3] The ensuing history has been interesting. This paper gives an overview of the progress of holography, from its origin until now. We note that the path has not been a uniformly ascending one.

As is well known, Gabor came to holography in a most ingenious way: to correct the spherical aberration of the electron microscope. At that time, the magnetic field lenses of the electron micsroscope had spherical aberration that could not be corrected. So Gabor proposed to record the entire wavefield, both amplitude and phase, and regenerate the same wavefield at optical wavelengths, where lens aberration correction techniques could be applied. The idea was not successful, although from time to time there have been papers describing the successful holographic recording of electron wavefields.[4] But purely optical holography began to be investigated as a new and interesting concept. Indeed Gabor made holograms at optical wavelengths, with optical waves being used also for the readout process, or, as it is commonly stated, the holograms were "reconstructed" at optical wavelengths.

Certainly the idea of recording a wavefield on photographic film and regenerating the wavefield from the recording was an intriguing one, and a number of researchers in Europe and the United States began exploring it. Early holographers of the late 1940's and early 1950s included G. L. Rogers,[5] M. Haine and T. Mulvey,[6] J. Dyson[7] M. Buerger,[8] and W. Bragg[9] in Europe. In the United States, P. Kirkpatrick and his students H. M. A. El-Sum and A. Baez took up holography,[10,11] and El-Sum became the first of many to do a doctoral dissertation on holography. In 1956 A. Lohmann applied communication theory concepts to holography, proposing the single-sideband method of eliminating the twin image.[12]

Many interesting issues were taken up in those early papers, the major one being how to eliminate the twin image that seemed to be an unavoidable consequence of the process. After a few years, interest in "wavefront reconstruction," as it was then called, waned so that by 1955 the paper rate declined to nearly zero. The principal reason for the decline was the poor image quality, resulting from a variety of causes, including the twin image, the self-interference term, and other extraneous terms resulting from nonlinearities in the recording process. The various proposed techniques failed to significantly improve the image quality. The holography eclipse remained for the next seven or so years.

Radar Holography

There was, however, a strange kind of revival that started in 1956, but under military security. We refer to synthetic aperture radar (SAR). In this technique, an airplane carries a sidelooking radar that illuminates the terrain. The pulse returns are stored both in phase and amplitude and are then processed in a manner corresponding to the way they would be combined on a large receiving antenna. Thus, the effect of a large antenna is produced, with resolution corresponding to an aperture many times larger than that of the actual antenna. This development was funded by the United States military and was secret.

There is of course a similarity to holography, and when the data are stored on photographic film and processed in an optical processing system, the similarity becomes quite striking. The heart of the analogy is that when the recorded radar data are illuminated with a beam of coherent light, the wavefield recorded along the flight path is then reconstructed, greatly reduced in scale and at visible wavelengths. For example, data gathered along a kilometer of flight path might be recorded on only several centimeters of film, and the original wavelength, about a centimeter in length, is reproduced on a similarly reduced scale, at about 0.0005 or 0.0006 mm. The data film thus forms an image of the illuminated terrain.

It should be stressed that synthetic aperture radar does not, in any way, derive from holography. Indeed, the recording of a total wavefield, both phase and amplitude, was never an issue in radio communcation systems. It had been done routinely for many decades prior to the invention of holography. What was routine in electronic systems was not so easily done at optical frequencies, where one cannot record the instantaneous signal but must record a time-averaged signal. The direct ancestry of SAR lay in Doppler radar, which was highly developed in World War II.

However, the application of holographic ideas to SAR, when the data were processed optically, led to highly sophisticated optical processing techniques with some excellent imagery being produced. By 1960, the holographic theory of SAR became dominant over the original SAR

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theory, such as Doppler filtering and cross-correlation. This hidden holography became visible to the general optical community only after 1966.[13,14] It is strange that, for a short period of time, between 1959 and 1962, holography was better known to radar scientist than to optical scientists.

Rise of Modern Holography

The question was next considered, what could SAR technology, and more generally, communication theory, offer to holography? The 1962 paper of Leith and Upatnieks presented an extensive development of holography from a communications theory viewpoint and suggested the carrier frequency (or off-axis) method of holography.[15] The viewpoint presented there was that the conjugate image was a classic case of aliasing in the recording process, whereby two different spatial frequency components of the field were mapped into identical fringe patterns, and the cure was to introduce a carrier frequency in the recording process, which could readily be accomplished by bringing the reference beam around the object and combining it with the object beam at a sufficiently large angle. Some writers considered this work to be the application of SAR principles to holography, but the knowledgable reader will recognize that our paper described holography in the framework of chirp radar, not SAR.

The carrier frequency method succeeded in separating the twin images, and in addition, eliminated the self-interference term (sometimes called the intermodulation product term) as well as distortion terms resulting from nonlinearities in the recording process. It made possible, for the first time, holographic imagery of high quality, as was demonstrated in a follow-up paper published in 1963.[16]

Also, in the early 1960s the laser became available, which made possible the holography of solid, reflecting, 3-D objects, as opposed to the transparencies that had until that time been used for holography.[17] The striking 3-D imagery that resulted created widespread interest in holography, and the technique almost immediately became under investigation worldwide. The growth in holography, during 1963 to 1965 was quite explosive. The number of journal articles on holography jumped from nearly zero in the late 1950s to about 150 in 1965.

The 1960s were certainly the golden years for holography. The beginning of that decade opened the door, and over the rest of the decade came many more fundamental advances. The holographic complex spatial filter, and in particular, the matched filter, was one of the very early inventions of that decade, and one that was made at the University of Michigan's Willow Run Laboratories (now Erim), the birthplace of modern holography. Many people participated in that early development between 1961 and 1964, but three stand out as being the prime movers: C. Palermo, who contributed the essential idea; A. Kozma, who made the first reduction to practice, i.e., made the first holographic complex spatial filter[18] and A. VanderLugt, who brought the technique to its culmination, applying it to pattern recognition and character reading.[19]

Shortly afterward came a second major holographic invention: hologram interferometry. The earliest form, time average, was first described by Powell and Stetson, also of the Willow Run Laboratories.[20] There followed about a year later the other two basic forms—the double exposure and the real-time, but this time a number of groups independently and nearly simultaneously were the inventors: R. Brooks, L. Heflinger, and R. Wuerker;[21] Stetson and Powell again,[22] R. Collier, E. Doherty, and K. Pennington;[23] K. Haines and P. Hildebrand;[24] and J. Burch, A. Ennos, and R. Wilton.[25] Hologram inteferometry was a completely new form of interferometry in which one could obtain interference between two waves that had in fact existed at different times. Such interference was possible because the holographic process preserved the phase as well at the amplitude of each wave. This technique was heralded as the first genuine application for holography and was soon applied to a variety of problems, including tire testing, heat flow measurements, and debonds in airplane wing panels.

Another major invention of that era was optical phase conjugation for imaging through irregular media, a forerunner of the wideaspread optical phase conjugation technique of today. The idea was given in the initial holography paper of Leith and Upatnieks (1962) as a possible application for the conjugate image that had previously been the greatest problem of holography. It was noted that the conjugate image, so called because its phase is conjugate to that of the originally recorded wavefield, had this potentially useful application: If an irregular medium lies between the object and the hologram, the object wavefield will be distorted prior to being recorded. By reading out the conjugate wave and passing it in the reverse direction back through the irregular medium, the phase errors incurred on the first pass are cancelled in the second, and a sharply focused image appears at the position formerly occupied by the object when the hologram was recorded. It was not until the summer of 1965 that we got around to experimentally demonstrating this idea, but a successful demonstation was reported at the August 1965 SPIE meeting, and the published paper appeared shortly afterward.[26] About the same time, Kogelnik reported a similar demonstration.[27]

The idea languished for several years, primarily, because useful applications required a detecting medium faster and less cumbersome than photographic film. Such media became available in the 1970s in the form of, for example, nonlinear crystals, whereupon the phase conjugation method of imaging quickly became an important area of modern optics, as it remains today.

Volume Holography

Amid the vast activity in holography, several groups had the interesting idea of introducing the reference beam from the back side of the plate, with the intent of getting the reference beam out of the way so that a larger object field could be accommodated. The first report of this modification was given by A. Hoffmann et. al.[28] In the laboratory, J. Upatnieks set out to repeat this reported work. In transporting the developed hologram from one building to another at the research center, Upatnieks was astonished to glance at the hologram in sunlight and see the 3-D image formed in white light. The members of the research staff then studied this strange holographic image with curiosity. About the same time the production of a similar white light viewable hologram was reported by G. Stroke and A. Laybeyrie and yet again by N. Hartman. In the rush to the patent office, Hartman emerged the winner, since his results were obtained several months earlier than those of the other contenders.[29]

What these groups had accomplished, either by accident or design, was a demonstration of a basic holographic process invented a few years earlier by the Soviet scientist Yu. N. Denisyuk.[30,31] The Denisyuk papers of 1962 and 1963, originally in Russian and later in translation in *Optics and Spectroscopy*, described a technique that, along with the spatial carrier method, was to become one of the cornerstones of modern holography. By introducing the reference and object beams from opposite sides of the recording plate, the resulting fringe pattern became extremely fine, with spacing on the order of half the light wavelength, and the fringes, rather than cutting across the emulsion, ran nearly parallel to the surface. Thus, the hologram had significant structure, on the order of 20 or so recorded fringes, across the emulsion depth. Such a hologram has become known as a volume hologram (or alternatively, a Denisyuk hologram), and this depth-direction structure gives the hologram the capability of white light readout, similar to the color photography method of Lippman.

Although the Denisyuk papers were published in 1962 and 1963, it was not until 1965 that the optics world realized their significance. There are several reasons for this. First of all, holography became widely known only beginning in late 1963 and early 1964, when impressive 3-D holographic images began to be disseminated. Also, the English-translated Russian journal *Optics and Spectroscopy* had much less circulation than the principal United States optics journal, the *Journal of the Optical Society of America*, and there was of course a delay between the original publication and the English translation. In my own case, I had read the Denisyuk papers in 1965, but it was only after I had viewed the white light reconstruction of the Upatnieks hologram that it dawned on me that this was indeed exactly what Denisyuk was talking about. Today, of course, Denisyuk holograms are widely known and form a major part of display holography. Finally, in the United States patent granted to Hartman, the patent claims were of course greatly circumscribed by the prior art of the Denisyuk papers.

Further Course of Holography

Holography expanded in the late 1960s, and indeed had become the hottest area of research in all of optics. Many avenues were explored and many applications suggested. Holographic memories became a major area, and it was predicted by some that the holographic optical memory would become a major product. Hologram interferometry was heralded as a new kind of interferometry for which vast applications awaited. When the startlingly realistic holographic 3-D imaging was first demonstrated, it was at once recognized that display was the natural area for holographic development, and the holographic display area was envisioned to eventually include holographic cinema and television. The holographic microscope was explored. The number of potential applications for holography soared.

Holography was of course at this time oversold, and by 1969 the sponsors of holographic activities faced the reality that no significant products would be available in the near future. Also, a mild recession about that time in the United States caused contraction in research outlays. The next few years saw a decline in holographic research.

Holographic Revival

By 1973 there were signs of a turnaround. Researchers sought and found true applications. This time around the proposed applications were modest, realistic, and generally well thought out. Most notable among the applications was display holography. There had been gradual improvements in photographic processing techniques for Denisyuk volume holograms, which made them both brighter and less noisy. In addition, two new types of white light viewable holograms emerged: the Benton, or rainbow hologram, and the integral, or multiplex, hologram. These three white light viewing techniques, all complementary rather than competitive, combined to give a powerful stimulus to display holography.

The Benton hologram, first described in an *Optical Society of America* abstract in 1969, embodied a new method of white light viewability that did not require a thick, or volume, recording medium, enabling such holograms to be produced cheaply by replication processes.[32] This capability came at the expense of the loss of vertical parallax, but it was an attractive engineering tradeoff. Shortly afterward the now widely used holographic embossing technique was developed, so holograms could be pressed into inexpensive plastic sheets by machines that could generate thousands of square meters of holograms in an hour, at a cost of only a few cents per square centimeter.

In the 1960s a number of researchers developed methods for synthesizing holograms from conventional photographs, each taken from a slightly different view.[33–37] L. Cross and his colleagues, using these methods, devised the multiplex hologram, which when combined with the Benton white light method yielded yet another white light viewable hologram. Such holograms could be made inexpensively, from any object that could be photographed, and limited motion in the image was allowed Thus, as one viewed the hologram from different positions, the object could exhibit motion, such as in holographic portraiture, the nodding of the head, the waving of a hand, etc.

These advances led to the rise of a display holography commercial activity, which has gradually grown in the past 20 years into a modest but stable industry, and has made holography a household word. A significant portion of that business is based on the hologram as a security device—to dissuade counterfitting of such documents as credit cards. Thus the early prediction, that display would be the major application for holography, has come true, although it took many years for this to happen. High quality, relatively inexpensive white light viewable holograms were required, and it took many years for these requirements to be met. Current research in display holography centers on producing high quality color holograms, and carrying out holographic imaging in real time.

Further Applications

To the suprise of many old-time holographers, the once discarded holographic optical memory is making a serious comeback. Multiple holograms are being stored in thick photosensitive crystals, such as lithium niobate. The storage capability of such crystals is in theory quite impressive; a 1-cm cube crystal with resolution cells the size of a micrometer could in theory store 10^{12} pixels, although current practice falls far short of this goal. The rationale for the revival of holographic data storage is that the enabling technology has progressed in the past 25 years to the degree that at last the time for holographic memories has come. Lasers, crystals, and spatial light modulators, all of which would be essential components of a holographic memory system, have advanced considerably since the early days of holographic memory development.

The advances in electronic cameras over the past few decades has made electronic holography an attractive option for many applications. Hologram interferometry and related forms of laser interferometry are generally carried out today with electronic cameras as the recording medium, which opens the door to extensive computer processing. Interferometry in general has benefitted by electronic cameras and computer processing, and the benefits are perhaps greatest for hologram interferometry, because here both the data collection and data processing are more complex and difficult than with most other forms of interferometry.

Our own work of recent years, the use of holography to image through highly scattering media, has amply demonstrated the advantage of electronic cameras and computer processing. Using a scientific CCD cooled camera, we make, for a single experiment, up to 8000 holograms, all written within a few hours.[37] The holographic data is read into a computer, where the reconstruction process occurs and the resulting images stored in both amplitude and phase are subjected to extensive signal processing, requiring about 5 to 10 hours. Such processing is carried out overnight, with the processed data awaiting inspection the next morning. The processing involves, besides the basic holographic reconstruction process, phase unwrapping a noisy signal, gating by correlation methods, phase and amplitude averaging, and spectral and spatial Fourier decompostion and synthesis. This level of sophistication in the holographic process was unthinkable in the early days of holography.

To the applications we have already noted, we add several others that collectively constitute the mainstream of modern holography. Diffractive optical elements (DOEs) that work on the basis of diffraction instead of refraction, have become an important branch of optical technology, supplementing the traditional refraction optical element. In addition to diffractive lenses, there are more general diffraction devices that perform operations that could be done with refractive optics only with great difficulty, if at all. Such devices include phase corrector plates that may be deposited on the surface of conventional optical elements and can correct the aberrations of the lens, or DOEs may rearrange the distribution of light in a beam, converting a Gaussian-profile beam into one with a uniform profile, with very little loss of light. The applications are novel and seemingly endless. Holography forms a significant part of this burgeoning diffractive optics technology, being one of various ways to produce diffractive devices along with others such as the binary optics and the kinoform processes.

Optical computing, including optical neural networks, is a relatively new area of optics. The hope has been that photons instead of electrons could form the basis for a new digital computer technology. Whether this technology will be successful is uncertain at this time. However, what is much more certain is that should the optical computer become a reality, holography will play a significant role, just as it does in optical analog computing processes (e.g., holographic spatial filters). Indeed, holography has been proposed for implementation of various elements of the optical computer. It has been supposed that an optical computer should have an abundance of interconnects, and various holographic solutions to the interconnect problem have been explored. Holographic optical memories, of course, would have their role in the optical digital computer. Optical logic devices based on holography have been invented. Such holographic applications must now await the arrival of the optical digital computer.

Holography, in one form or another, reaches into many diverse areas of optics. It has become a versatile and useful area of modern optics.

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