HOLOGRAPHY

Lloyd Huff

Chairman/Editor

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Chairman/Editor

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Session 1

Displays, Materials, and Techniques

Chairman
Lloyd Huff
University of Dayton Research Institute

Keynote Address

Holography-The Promise Fulfilled

Emmett N. Leith

The University of Michigan
Ann Arbor, Michigan, 48109

Abstract

Holography, after some oscillation in its early history, appears to have settled down to a pattern of sustained growth. Commercially important applications are emerging.

Introduction

A process so completely incredible as this should find many uses, was my assessment when I first became acquainted with holography, then called wavefront reconstruction. Perhaps the early workers in holography, such as Haine[1], Dyson[2], Rogers[3], and indeed Gabor[4] himself thought so, too. Certainly this thought was in the minds of the throngs of researchers who entered the field in the early 1960's, captivated by the quite dramatic 3D holographic imagery that had just been demonstrated. For the most part, however, the applications proved elusive. Now the situation is slowly changing, as the long awaited applications continue to emerge.

The early surges

Historically, the development of holography can be likened to an underdamped system, with two well defined oscillations having already occurred. The initial enthusiasm that followed Gabor's announcement of this new concept of image formation lasted several years, but then faded. I think the poor quality of the imagery was chiefly to blame, but also faulty were the applications then being proposed, such as 2-step electron and x-ray microscopy. Historically, it appears that other, more feasible applications, that could have succeeded at the time, might have carried holography on to a slow, sustained development. Finally, the light sources available at the time were a decided limitation, although not at all to the extent that is sometimes supposed.

By the mid 1950's, the first surge of holography had run its course, and activity had fallen off to a very low level indeed.[5] The first cycle of the oscillation was now complete. At the same time, events were gradually building for the second surge.

This began inauspiciously in 1955, when the concepts of holography were applied to the fast developing process of synthetic aperture radar (SAR). It was then noted that SAR was similar to holography, and that the optical processing that contributed so enormously to the success of SAR could benefit by application of holographic concepts. Extensive cross fertilization between SAR and holography was beneficial to both areas. In particular, holographic concepts offered, first of all, a new, strikingly different, and very physical way of understanding SAR. Second, holographic concepts led to the development of some very important and unique optical processors, most significantly, the tilted plane optical processor.

During the period 1956-60, the holographic viewpoint rose to become the standard way of describing SAR. In the process, hundreds of radar specialists became knowledgeable about holography. This new awareness of holography had no visibility in the open literature, since SAR was DOD classified.

Also, the rise of holographic concepts is by no means equatable to a rise in holography. SAR is like holography, but its practitioners do not regard it as holography, and rightly so. Its lineage is wholly different from holography; the underlying concepts that it shares with holography, i.e., the recording and storage of phase, did not stem from holography, but rather from other forms of pulse doppler radar, which in fact predate holography. Thus, one might say, perhaps paradoxically, that holographic concepts were rejuvenated, but not holography.

True holography, however, did have a rejuvenation in the shadow of SAR. The theory of off-axis holography, first developed in connection with SAR, was extended to holography at the beginning of the 1960's. This work came into the open with our presentation at the Fall 1961 meeting of OSA, where, among other accomplishments, off-axis holography was described; we called it carrier frequency holography, and still consider that to be the best and most correct term.[6] In addition, in the 1961-62 period, Fourier transform holograms were constructed and used as spatial matched filters, again, the first application being for optical processing of radar data.[7]

This early off-axis holography was carried out in the prelaser era, with only a mercury arc source and sometimes with a digital computer. Computer generated holograms, of course, required no laser, and if the objects are only transparencies, the mercury or arc source is quite adequate for making holograms. Indeed, as later work has demonstrated, broadband light sources, several hundred angstroms in bandwidth, can do just as well as, possibly better than, the laser in making either Fresnel or Fraunhofer holograms, although not as easily. For holograms of transparencies, the advantage of the laser is principally that less skill is required; in general the less coherent the source, the greater is the interferometry skill required for holography.

The helium-neon laser, first commercially available in 1962, presented several advantages for holography, the principle one being that holography of 3D, reflecting, real world objects now became feasible. This accomplishment was widely publicized over a four month period, beginning in December 1963 and culminating with a paper and display at the April 1964 meeting of the OSA. The demonstration of unbelievably realistic 3D imagery gave enormous impetus to the new surge of holography that had been building. The activity in holography became frantic, as many hundreds of opticists throughout the world turned their attention to this fascinating young science. In the next few years, holography reached the zenith of its second oscillation, whose amplitude exceeded that of the first by several orders of magnitude.

An impressive army of researchers, convinced that such remarkable imagery would lead to important applications, explored holography with a thoroughness this area had not before seen. They came up with proposed applications too numerous to mention. It turned out that holography could do far more than anyone could have imagined, from interferometry and spectroscopy, to data storage and image processing. Unfortunately, it generally could not perform these applications nearly as well as the traditional optical methods, a fact that became more apparent in the ensuing years. So, by the end of the 1960's activity in holography diminished, with only a handful of genuine applications having been uncovered. The second great oscillation of holograpy was nearing completion.

The major application was hologram interferometry, and it is even today probably the most important application. By its nature, hologram interferometry has low visibility; it results in no holographic products, and the practitioners are in small, widely dispersed groups. Only when they are occasionally flushed out, as when enticed by a conference on hologram interferometry, does the considerable extent of this activity become evident.

Hologram interferometry was a very early application, stemming from 1965.[8-11] It was hailed as the first of a long line of anticipated applications. The sequels, however, came very slowly. Holographic optical memories would, it was supposed, be the second; the reasoning went: optical memories have much to offer, but the full advantage of optical memories can be realized only with holography. As it turned out, optical memories were indeed viable, but only in the nonholographic mode.

Holographic displays, it was assumed, would be a major application for holography; after all, it was the holographic display that created the explosion in holography. Unfortunately, good display holograms were expensive, as were the light sources required for viewing them.

Spatial filtering was, in a limited sense, perhaps the earliest genuine application for holography, since the aforementioned applications to optical processing of radar data were quite real. They were, however, rather limited and esoteric applications. The larger, hoped for applications of the holographic filter, viz, automatic character reading and pattern recognition, ran into competition with the digital computer, which won out because, as it turned out, matched filtering, the forte of the holographic approach, was found to be not the most suitable method for those applications.

Even though holographic activity diminished, it still remained at a respectable level, with never less than several hundred papers being published each year in the optical journals. And, after several years of leveling-off, a new upward trend in holographic activity became apparent by the mid 1970's. It was, in contrast to the earlier growth, a slow deliberate effort. Some of the previously proposed applications areas were gradually achieving viability. The new successes were partly the result of improved technology, which made previously impractical proposals become practical, and partly the result of intense investigation by many serious researchers, who knew quite well both their application requirements and the capabilities of holography.

The variable level of holographic activity is depicted in Fig. 1; the curve is of course rather subjective. The most controversial portion of the curve is the part depicting where we are at presently. Should the measure of holographic activity be the number of papers published, the amount of money being put into holography, the profit being derived from holography, or the rate of hologram production? If the latter is to be the measure, then the "today" part of the curve should be several orders of magnitude higher than we have shown.

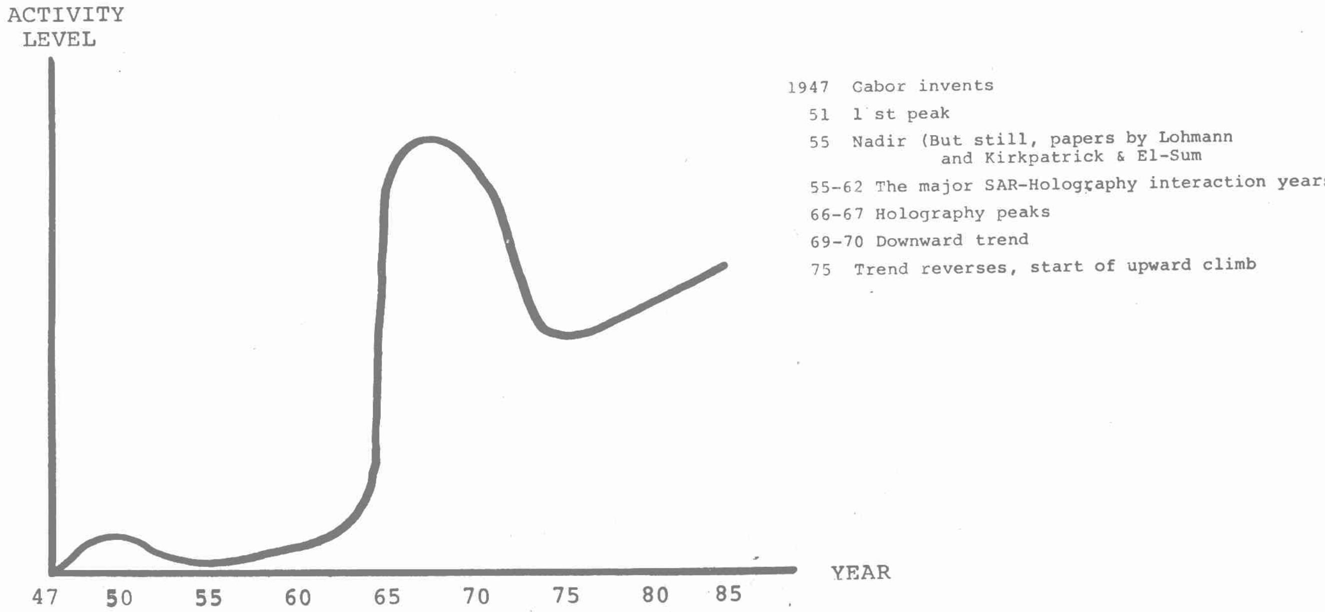

Figure 1. The fortunes of holography.

The emergence of display holography

Displays had been since 1964 the natural application for holography. It had been the 3-D displays that attracted most researchers into holography, and certainly holographic 3-D surpasses all other types of 3-D imagery. But two ingredients had been lacking; first, a white light readout process, and second, a means for making inexpensive copies.

Two factors called for white light readout: all monochromatic sources, such as lasers and mercury arcs, are expensive, and also, images simply look unnatural under monochromatic illumination. Denisyuk's 1962 method, not demonstrated with arbitrary, 3-D objects until 1965, appeared to provide an answer, although the perfection of the process took many years.[13] What was needed was improvement in diffraction efficiency and reduction of scattered noise. The Soviets concentrated on the Denisyuk method, producing by 1975 holograms of excellent brightness and so scatter free that the best of their Denisyuk holograms have the appearance of actual objects imbedded in crystal-clear glass. In the West, Nicklaus Phillips of Britain is widely recognized for his pioneering efforts in producing low noise Denisyuk holograms.[14] The principle factor is the use of extremely fine emulsions, along with development processes that produce minimum enlargement of the grains. In the United States, dichromated gelatin has yielded excellent holograms, combining high diffraction efficiency with low noise.

The Benton rainbow hologram, utilizing a wholly different white light readout principle, was a valuable complement to the Denisyuk method, and along with Cross's multiplex hologram, which also used the Benton white light readout method, enormously enlarged the scope of white light holography.[15] Using these white light holograms, display holographers set about making holography a household word. Holographic displays became commonplace and more widely acclaimed. But such holograms tended to be rather expensive, except in the small pendant sizes. A technique of inexpensive reproduction was needed. The Denisyuk hologram, being a volume structure, did not lend itself to inexpensive replication. But the Benton hologram did, and several well conceived efforts to develop such methods arose. It had been felt that holograms, at some pricing level, had a mass market potential, and efforts over the past decade to achieve such a level resulted in the highly perfected embossed holograms that we see today. For example, about 11 million holograms were produced for the cover of the March issue of National Geographic, at a cost reputed to be several cents each. Examination with a reasonably small light source (e.g., a microscope illuminator) reveals the holograms to be of superb quality. In addition, they are extremely bright. High quality embossed Benton holograms have the property, absolutely remarkable from an historical viewpoint, that, when hung on the wall for viewing purposes, they exhibit in certain directions a reflectivity considerably higher than that of the wall itself, or of a conventional picture hung on the wall. In short, they look dazzingly bright under moderate illumination levels.

Much of the credit for the success of display holography belongs to independent holographers functioning outside the established companies. Working in small groups, of one to perhaps a dozen persons, they simultaneously assumed both technical and entrepreneurial roles. They perfected the techniques, conceived products, and tested the marketplace. Their contribution to display holography is enormous.

Although there is still room for improvement, display holography is today everything that one, back in the 1960's, could have wished it to be. Perhaps the greatest drawback is that the holograms display most effectively in gallerys, where the holographic expert has full control over the illumination and can cause the observer to be at precisely the correct position. Outside the gallery, it is somewhat chancey whether the observer will illuminate and view the hologram properly. On balance, it appears that display holography has at last reached the stage where it can become economically a major part of holography.

Holographic optical elements

Optical elements are another area where holography has become firmly established. The holographic optical element (HOE) can assume one of three forms: a grating, a diffraction lens, or a beam splitter or combiner. Commercially this is the area that has seen the greatest growth during the past decade.

Holographic gratings have been a commercial product for more than a decade. They have been considered as one of the major successes of holography. Certainly a success, but truly holography? Is the photographic record of the interference formed by two collimated light beams really a hologram? If so, then holography must be far older that Gabor. Birch reported in 1960[16] the making of diffraction gratings by recording two interference patterns, and the grating like nature of recorded interference patterns had been noted much earlier than that.[17] Indeed, it must have been recognized since the very beginning of photography.

I cannot think of any justification for calling a recording of a simple two beam interference pattern a hologram. On the other hand, if at least one of the two interfering beams had been modulated with some phase factor $\phi(x,y)$ that had been deliberately imposed, with a view to incorporating that phase factor into the grating structure, then the grating could justifiably be called a hologram.

For example, sophisticated holographic scanners may incorporate complex phase factors, representing small but crucial deviations from simple grating structures, thus fully incorporating holographic technology into their design and construction. Such functions are needed in order that the beam can traverse a precise, not necessarily linear, path, and can be precisely focused at all points along the path.

Similarly, the interference between a spherical wave and a plane wave (or another spherical wave) produces a Fresnel zone plate structure; we do not need the teachings of holography to tell us that. However, when we recognize that when the FZP is illuminated with a duplicate of one of the interfering waves and one of the diffracting waves is a perfect regeneration of the other, and that almost any other readout geometry produces aberrated waves, then I think we are involved in holography. Similar arguments can be formulated when we produce volume recordings of interference from waves traveling in opposite directions; the resulting structures can justifiably be called holographic beam splitters or combiners in all but the most trivial situations.

I think that a wide range of valid viewpoints is possible as to how "holographic" the HOEs are, and I have offered here a somewhat middle of the road view. In any event, the HOE technology is quite healthy and must surely be the most rapidly growing area of holography.

Where holography is going

There are yet other applications for holography, some small but well established and respectable, and some struggling for viability. Perhaps a few of these will grow into major ones. Holographic particle sizing, for example, is a small but important one. Here, holography does what no rival technique can do. In addition, particle sizing has grown in importance over the past several decades. Some feel that the need for accurate, quantitative results over a wide range of particle types is not being met with today's particle sizing technology, and an increased role for the holographic devices, with their superior capabilities, may be in the offing.

Optical pattern recognition has struck out in new directions in an attempt to find a niche in a world increasingly dominated by electronic digital computers, resulting in some very intriguing innovations in holographic filters.

I predict that there will be no more oscillations in the development of holography, and that the present activity will continue monotonically increasing, following a curve that will be somewhere between an exponentially increasing function e^{jkt}, and an exponentially saturating function $k_1(1-e^{-jk_2t})$ (k's all positive constants). It seems inconceivable that holographic activity should ever again diminish; there are simply too many proven applications for that to happen.

However, the accuracy of these predictions may in the future become blurred as various areas of holography evolve until they are not necessarily holography anymore, or alternatively, new activities may spring into being that are like holography or genetically related to holography, yet may actually be a new species.

Phase conjugation is one such example, especially degenerative 4-wave mixing.[18] Here is an area that to a holographer looks much like holography, but the phase conjugationist points out that while the relationship is close up to a point, the degenerative 4-wave mixing process has some aspects with no counterpart in holography. The extent of the debt phase conjugation owes to holography is not clear. Nor is it even clear just where true holography stops and phase conjugation begins. However, it is becoming clearer that phase conjugation imaging will likely succeed in a practical sense, even though its predecessor, phase conjugation holography, failed until only recently to attain practical importance.

Holographic phase conjugation imaging began in 1965 with the demonstration that when a hologram is made using an object wavefront that has passed through an inhomogeneous, distorting medium, and when the conjugate wave is generated and is made to retrace the original optical path, the aberrations in the conjugate wave are compensated by the inhomogenieties of the optical path, and the hologram thus forms a perfect image, free from all aberration, provided the retracing is exact.[19,20] With holography, one can thus in a sense image through very inhomogeneous media, such as ground glass, whereas imaging through such media by conventional means is not possible.

At the time, it appeared that this new holographic technique would lead to numerous important applications. This never happened. There are several reasons, one of which is that, like all holography, this process is done in two steps, with a time delay and some tedious work between the two steps. But remove that time delay, make the overall process essentially instantaneous, and then the applications become manifest. With instantaneous response, the turbulent atmosphere can be the inhomogeneity, and the conjugate wave can retrace the path before it changes. Here is a new and exciting method to form high quality images under bad seeing conditions, an application that was never available to holography.

Will we see yet other trans-holography processes? Probably. The prospect is exciting, although indeed such processes might contribute little if anything to the image of holography, since they would likely not be perceived as extensions, or as offspring, of holography.

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Display Holography
An SPIE Critical Review of Technology

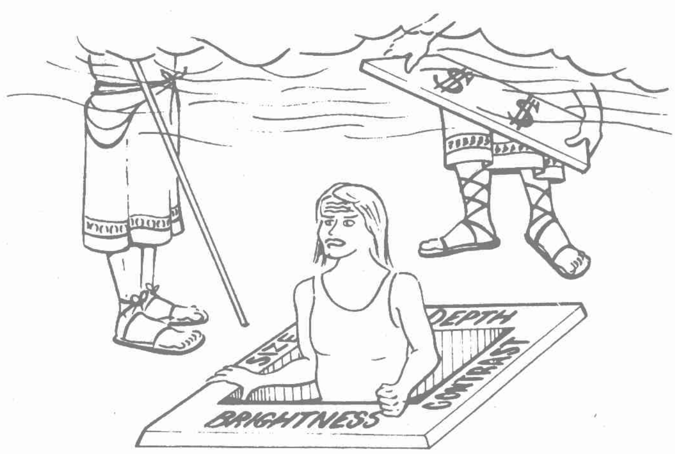
Stephen A. Benton

Research Laboratories, Polaroid Corporation, and
Media Laboratory, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

Introduction

Holography has been enjoying an explosion of public interest over the past two years, especially as the number of three-dimensional laser photographs in peoples' homes has increased dramatically. Underlying this public perception of progress has been an authentic and gradual development of holographic imaging technology, but it is fair to say that holographers are still struggling against the same fundamental constraints as they were more than ten years ago. In business, "timing is everything," and the recent events in holography are largely business phenomena (it has always taken a lot of patience to be a holographer, and no less so in these matters!). In this discussion, we will attempt to draw out a few of the long-term threads of holographic progress that underlie the recent good news.

The old problems are still the big problems. Figure 1 shows a new corner of Dante's visit to the Inferno, where Virgil shows him a holographer trapped in a box of technical constraints with walls labelled "image brightness", "image contrast", "image depth", and "hologram size." The holographer is free to approach any of these boundaries, but he cannot press against them all at the same time, and if he tries to escape through the top of the box, there awaits the lid of "dollar cost" to stop him again. Naturally, the box is also inhabited by many pests, such as "laser speckle" and "unreliable chemistry," but the hard outer walls are the same ones holographers have been struggling against for years. They are grounded in the fundamental properties of coherent light sources and of holographic materials. But the box has grown significantly since 1964, and some interesting holes have been worn into its walls, and that is the real story of holographic progress. It will be far easier to tell a story that highlights features that are apparent to casual viewers, such as the colors of the images and their motion, but the fundamental questions must underlie those superficialities. Holographers are slowly winning the freedom that their unique visual medium deserves, but our years in Purgatory are not quite over yet!



This discussion will be divided into four parts. Laser-transmission "Leith & Upatnieks" holography, white-light transmission "rainbow" or "Benton" holography, and reflection "Denisyuk" holography are the now-familiar formats for holographic imaging, each of which is finding its own unique role to play in practical displays. The subject of holographic stereograms, or the synthesis of apparently holographic images from a sequence of photographs, enters into all three formats, and so will be introduced first, and highlighted again as it arises in subsequent sections.

Holographic Stereograms

In its basic forms, holography produces roughly same-size images of objects that can stand extremely still during the exposure. The choice of "hologenic" subjects has been an important part of the holographer's craft: they are primarily small dead subjects. The use of pulsed lasers, such as ruby or frequency-doubled Nd:YAG, widens the scope of holography to include live human beings. But the production of magnified or minified images without spatial distortion, such as moving human beings at pendant size, or the use of computer-graphics imagery and the dazzling visual effects we have come to expect from modern media, all these have awaited the development of practical techniques for what we call "holographic stereograms." By recording large numbers of perspective views from side-to-side (and less often from up-to-down) on photographic film (or video tape) in ordinary light, and later projecting these onto holographic film with laser light, an apparently continuous sweep of parallax, such as provided by a normal hologram, can be presented to a viewer.

A holographic sterogram is only an approximation to a laser hologram, one that exploits the particular visual characteristics of human observers, but good ones can have most of the 3-D impact of real laser holograms. The ability to incorporate arbitrary subject matter, to manipulate it with well-understood film methods, and especially the fact that image designers need understand almost nothing about holographic physics to make effective images, enormously expands the audience for holographic imaging. Holographic stereography also offers holographers new aspects of control of their medium that diffraction optics often denies them, such as the achromatization of images over substantial depths, and new possibilities for full-color rendition.

Returning to our theme, holographic stereograms are anything but a new research topic (1). Work in the field goes back to the late Robert Pole in 1966 (2), and developed quickly in subsequent years. A particular technique of current interest is a refinement of the method of King, Berry & Noll, published 15 years ago (3), that takes fuller account of the detailed chromatic variations of diffraction optics (4). Combined with advances in experimental technique, new approaches have yielded holographic stereograms of astonishing impact, and suggest that stereographic methods will play a growing role in the future of holographic imaging. Specific examples will be mentioned as we go on to discuss each format in turn.

Laser Transmission Holography

Refinements of the Leith & Upatnieks off-axis method, and even the Gabor in-line method, continue to produce the most impressive depth and detail in holography. In situations that permit laser illumination of holograms for viewing, these are the "holographer's holograms." The wider understanding of "phase conjugation" (also known as "reverse ray tracing") has led to an impressive series of real-image projections that extend dramatically into the viewer's space, such as those in the "Pavilion of the Imagination" at Disney's EPCOT (5). A major part of their impact is due to the large size of the holograms, roughly 1.0 x 1.5 meters, which is in turn due to the manufacture of film a meter wide, and the development of technology to successfully expose and process large areas of flexible materials. There are only three or so laboratories in the world with facilities large enough to handle this type of work.

A second holographic recording of the projected 3-D image allows that image to straddle the image plane, a so-called "image plane hologram" (aka. "full-aperture transfer") (6). If the depth is only a few centimeters, these can be viewed with white light with reasonable results. Dispersion pre-compensation by a tandem grating can extend the useful depth by several times, as described by DeBitetto in 1966(7), and more recently by New Holographic Design, Ltd (8). However, the need for large-diameter collimating optics for precise work has limited the sizes of such holograms to about 50 cm on a side.

In 1969, Dominick DeBitetto showed how a sequence of photographs could form side-by-side strip holograms to make a simple holographic stereogram (9). Much recent work can be traced to DeBitetto's early ideas. But simply scaling these composites up to 50 cm height by a meter long brings them a strong visual power, as recently shown by Outwater and his associates at Advanced Dimensional Design, Inc. (10).

The technical, financial and legal complications involved with laser presentation of holograms have stimulated substantial interest in holograms meant for non-laser viewing. Mercury arcs have been effective laser replacements on a small scale, but the use of common white-light sources, such as spotlights or the sun, has become especially attractive, though usually at the cost of image quality. To regain image brightness, depth, resolution and angle of view, we must design new types of holograms that are intended, from the start, for white-light viewing. This brings us to the subjects of white-light transmission or "rainbow" holograms and reflection holograms.

White Light Transmission Holograms

Our eyes are separated horizontally, and we move about our environments mostly in a horizontal plane, and so it is that horizontal parallax, the variation in perspective with horizontal viewpoint changes, conveys so many cues to our perception of distance and spatial relationships. The elimination of the (relatively ineffective) vertical parallax information not only greatly lessens the information load on the hologram, but can also reduce the spatial and temporal coherence required of the viewing light source. Elimination of vertical parallax is also a venerable topic in holography, but it wasn't until our work in 1968 merged this with image-plane holography that a practical method was found (11). At first, we thought that this would be the solution to holographic television, which seemed to be just around the corner, but it gradually became evident that it was the production of bright, deep & sharp images with white-light illumination that was going to be more immediately important. Sinlge- and multiple-color "rainbow" holograms have since become a favorite of artists, especially in the New York area, and multi-color rainbow holograms up to a meter square are being made routinely in France (12). While it is possible to make rainbow holograms in one step (13), with large lenses or mirrors, the controls afforded by the two-hologram technique have made that the method of choice.

Because their diffraction depends only on a simple modulation of phase, rainbow holograms can have a structure that is purely surface relief. The lower diffraction efficiency of this type of structure is made up for by the inherently high luminance of rainbow holographic images, due to their use of the entire spectrum and the limited solid angle that their light is diffracted over. An important practical advantage is that surface-relief holograms are readily replicated at very low cost by embossing or casting the relief pattern into clear plastic, as developed by Hannan et.al. at RCA (14), following a suggestion by Hendrik Gerritsen in 1965 that "holograms ought to be as easy to reproduce as LP records, and by similar technologies" (15). This approach was extended to rainbow holograms with a metallized layer (so-called "reflective rainbows") by Michael Foster around 1974 (16), and then lay dormant for a few years until developed as decorative stickers by Stephen McGrew (17). These began to be used by artists (notably John Kaufmann and Dan Schweitzer) in 1980, and were incorporated as a promotional item for a candy (Reese's Pieces' "E..T." promotion) in October 1982. "Reflective rainbow" stickers were also hand-applied to record albums (UB-40, July 1982) and magazine covers (Amateur Photographer, 25 June 1983) in England.

In 1980, the US Federal Reserve Board commissioned studies on holograms as counterfeiting deterrents for paper currency. This led to the development, largely by the American Bank Note Company, of very thin embossed "reflective rainbow" holograms in the form of a foil for hot-stamp application. Because they are readily applied in large quantities by automatic machinery (and difficult to counterfeit), reflective rainbow holograms have been adopted by MasterCard, and subsequently VISA, as security features on their credit cards, which will place close to 190 million small holograms in people's wallets all around the world. The same cost and throughput features have made the technology attractive to large-scale publishers, such as the National Geographic magazine, whose March 1984 issue featured a reflective rainbow hologram of an eagle on its cover, and a comprehensive article on holography inside, bringing a first-hand experience of holography to about 40 million readers in a few weeks (a second holographic cover is planned for late 1985).

As proud as all holographers are to see these images gain world-wide recognition, it needs to be said that their image quality falls somewhat short of what we hope for the future of this new imaging medium. The "mirrorized" nature of the stickers reflects a great deal of background light into the image, making it sometimes difficult to see, so that the subject matter must be easily identifiable. The practical necessity that the hologram "must work in any light!" severely restricts the depth that can be used. Thus the design of images for these holograms takes on its own special set of aesthetic as well as technical challenges. We can only hope that trends in interior lighting continue to favor spot-lit task-oriented lighting!

The principles of holographic stereograms were applied early to rainbow holography, such as by Redman and Wolton in 1970 (18). In 1973, Lloyd Cross merged three lines of research to produce a cylindrical rainbow holographic stereogram he called the "Multiplex" hologram, which was produced in a single repeated-projection step (19). This "lampshade" format hologram, with a clear incandescent lamp below, and its characteristic prominent vertical stripe pattern, became popular due to the availability of relatively inexpensive "proximity copies" (although an unfortunate choice of processing chemistry is causing a degradation of many of these copies today). Despite the appeal of their 3-D content with motion, the limited resolution of the images, and some inherent severe distortions, have caused a decline in their popularity in the U.S.A., although there is a fresh interest growing in Japan.

The "de-rainbowing" of white-light transmission holograms takes the story in another direction. By providing an achromatized "neutral" image tone ("black-and-white"), holograms have begun to render objects in ways that can be accepted as near to reality. This is stimulating a recent movement toward photographic-style imaging, which is also driven by the newer holographic stereogram methods. Our recent work (4), for example, which brings a deeper analysis of diffraction optics to the type of hologram proposed by King, Noll and Berry (3), produces an image that is 20 cm square by 50 cm deep or more, with good tone neutrality. We expect this direction of research to widen to include the realistic rendering of computer-generated images (CAD/CAM, medical, architectural etc.) as a new form of totally synthetic holography.

With the control of image color tone comes the hope for extension to full-color imaging (20,21), and this has been demonstrated in a kind of "peep-hole view" way for several types of multi-rainbow holograms, usually made in one step (22). Full, natural color is still beyond our grasp, but the brightest near-term hope for it still seems to lie with reflection holography.

Reflection Holography

By introducing the reference beam through the back of the holographic emulsion during exposure, an evenly spaced "stack" of diffracting layers is created that, in the processed hologram, serves as a narrow-band mirror to reflect only a single color of light. Thus, as Denisyuk showed in 1962 (23), a white-light point source can be used to view an image that has full parallax, vertical as well as horizontal variations of perspective view. Subsequently, "full-aperture transfers" have made hologram-straddling images possible, which extend into the viewer's space (24). Hundred's of thousands of reflection holograms were manufactured in the late 1960's by Conductron Corp. (later acquired by McDonnell-Douglas) using a step-and-repeat process with roll film. Recently, Applied Holographics, Ltd., of England, has proposed another form of high-volume holographic copier (25).

If the spacing of the hologram reflecting "stack" is deliberately varied from back to front, and the index modulation is high enough, a wide band of wavelengths can be reflected, producing a nearly neutral-toned image ("gold tone" & "silver tone" for example) (26). Holographic dichromated gelatin was invented at Bell Labs by Shankoff (27), and developed for holographic optical elements at Hughes Research Laboratories (28). It was refined for decorative imaging by Richard Rallison, emphasizing the wide-band reflectance mode, around 1974 (29). Until recently, his reflection holographic pendants, belt buckles, and other jewelry items were the most widely seen form of holography. Dichromated gelatin can also be processed to yield narrow-band holograms, but the need for high levels of blue exposing light has limited its use outside of industrial laboratories. Recent progress in red-sensitized, film-based synthetic photo-polymers that are easily processed holds promise for wider applications of this type of volume phase hologram (30).

Pure-color reflection holography tends to be based on silver-halide materials, which require much less light for exposure, have better understood chemistries, and are more stable after processing. An interesting technique for producing several different color images from exposures with a single-colored laser, based on swelling the emulsion between exposures, has recently emerged. This "reflection pseudo-color" technique was invented independently by Jeff Blyth in the UK (31), and P.M. Hariharan in Australia (32). It has since been adopted by several artists and commercial workers (33,34). Although the luminance of each image goes down as additional exposures are superimposed, three-color images have been attained with good visibility and acceptable registration of the component colors. The reliability of improved processes, such as van Renesse's "Pyrochrome," (35), is especially important here.