The Hologram and Its Ophthalmic Potential

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THE HOLOGRAM AND ITS OPHTHALMIC POTENTIAL*

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A review of recent advancements in holography generates far more than academic interest for the professional in the ophthalmic field. The uniqueness of the image storing and forming properties of the hologram suggests many exciting research and clinical applications.

The orthodox photographic recording of an object field involves the object field, its illumination and radiation, an optical imaging system, and a detector (film). While the object may be three dimensional, only a two dimensional facsimile is formed and recorded: an energy level is registered for each object point as an image point.

Several significant differences exist between viewing the original object space and the imaged field. While the three dimensional object field permits the observer to change perspective and to recognize parallax effects, the two dimensional photographic recording does not. Further, the angular energy distribution radiated from any given object point is determined by the nature of the object surfaces: while these distributions may be appreciated by the viewer of the object as texture, the spatially modulated amplitude recording (photograph) does not afford this evaluation.

The objective of this paper is to describe and discuss holography, a recording and viewing technic which provides an image field possessing every attribute of the original object field.

Assuming, for the sake of simplicity, the coherent illumination of an object, one may visualize that each object point radiates light waves as expanding spherical wavefronts. In any given reference plane all of these wavefronts manifest a composite complex electromagnetic field, with each elemental wavefront possessing properties of relative phase and amplitude which are characteristic of the object.

If one were able to arrest this ever-expanding electromagnetic field and record phase and amplitude information in a given reference plane, all of the information which is uniquely characteristic of the ex-

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exciting state—the object—would have been preserved. The relative phase of any elemental wavefront and its obliquity to the reference plane is determined by the relative position in space occupied by the radiating object point, while the amplitude of the light wave is determined by that point’s reflectance, and the distance of the elemental wavefront from the point.
While both film and retina are sensitive to intensity, neither can detect phase, and therefore this channel of information, proceeding from the object field, is forfeited. Interferometry, however, offers a technic for encoding these phase differences as spatial intensity modulations—fringe patterns—which are readily detectable by either film or retina. Such an interferogram, containing both phase and amplitude information uniquely characteristic of the object field, is, in essence, a hologram.

The earlier speculated arrestment of the expanding electromagnetic field has indeed been accomplished:

THE HOLOGRAM

The concept of the hologram was first described by Dennis Gabor\textsuperscript{1} in 1949 and later developed by Leith.\textsuperscript{2} The physical mechanism underlying the formation of a hologram is essentially that which is embodied in the interferometer depicted in Figure 1.

The superposition of coherent collimated beams A and B at included angle $\alpha$ results in an alternation of constructive and destructive interference, which in turn, manifests bright and dark fringes (straight) respectively. It may be seen from Figure 2a that for a given angle $\alpha$, the spacing between bright or dark fringes in reference plane OC depends upon incrementation of one wavelength path difference between beams.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Fig. 1.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{Fig. 2a.}
\end{figure}
A and B. Wavefronts from each beam arriving in phase interfere constructively, producing an amplitude greater than either of the two individual amplitudes (Figure 3a): where waves arrive out of phase by one-half wavelength, destructive interference results in a cancellation of amplitude (Figure 3b). Superposition of waves of intermediate phase relationships (Figure 3c), and/or unequal amplitudes, will result in intermediate amplitudes—or as observed or recorded, intermediate spatial intensities.

A comparison of Figures 2a and 2b reveals that an increase in the angle included between beams A and B (angle \( \alpha \)), produces an increase in the maximum path difference at 0 and results in an increase in frequency of alternation or a reduction of the fringe spacing.

The resolution or definition of the fringes is dependent upon several factors worth noting. If the light source is physically broad or extended, it consists of many point sources. Each "point" produces a pair of beams, A and B, angularly displaced from another pair of beams to an extent which depends upon the separation of the "point sources." Further, the relative phases of trains of waves proceeding from each point, at any given time, are completely independent of each other. With each point producing a set of fringes, the consequence of a relatively broad source is, at best, a composite set of fuzzy or smeared fringes. The condition which the point source satisfies is referred to as spatial coherence.

Recalling that fringe spacing depends upon a one wavelength increment of path length difference it follows that as chromaticity or wavelength is varied, the fringe spacing varies in direct proportion. The consequence, therefore, of a source which is not strictly monochromatic, is a broadening or a loss of definition in the fringe pattern. The condition of extreme narrow-banded monochromaticity is referred to as temporal coherence. It is feasible, however, to employ three narrow-band sources such as the primary colors, to construct a hologram, which
when appropriately illuminated and viewed, will afford a full color image reconstruction.

The simply stated requisites for spatial and temporal coherence belie their severity which, in fact, finds all ordinary light sources inadequate for use in holography except in very special circumstances. The recent advent of the laser, however, with its extreme narrow-band, high energy output, and high degree of collimation, provides light sources which admirably satisfy both spatial and temporal coherence criteria.

Figure 4 depicts the schematic substitution of a laser source and a complex object for the collimated point source and mirror $M_1$ of
Figure 1. Just as each point on the plane mirror $M_1$ (Figure 1) serves as a source of radiating spherical wavefronts, so functions each point on the complex object surface. Figure 5 demonstrates how each point's location in space determines the obliquity of its spherical wavefront to reference beam $A$ which, in turn, governs the resultant fringe spacing. It is worth noting that the wavefront from point 2 has a greater angle of obliquity relative to reference beam $A$ than does point 1. As such, their respective fringe spacing demonstrates the same inverse dependence on obliquity to the reference beam as is illustrated in Figures 2a and 2b, i.e., the greater the angle, the smaller the fringe spacing. The reflectance of each point determines the amplitude of its signal bearing
radiation propagated within beam B, Figure 4. This information is stored for each point by virtue of the contrast it imparts to the fringe pattern because, for a given relative phase, the relative amplitudes of superposed signal bearing and reference wavefronts determine the extent to which extinction or reinforcement of destructive and constructive interference, respectively, take place.

To recapitulate, both amplitude and phase have been recorded in the hologram. Further, since the signal bearing radiation from each point reaches every point on the hologram, each of the latter point locations contains, in its complex interferometric pattern, essentially the same information. It is interesting to note that if a hologram is broken, any small piece can be used to reconstruct the entire image.

Figure 6 is a hologram of three vacuum tubes. It cannot escape one's notice that the hologram imparts no clues to the viewer of its relationship to the original object.

IMAGE RECONSTRUCTION

A decoding or signal extraction technic may be exercised on the hologram to reconstruct the original "exciting state"—the object. The hologram may be employed, as illustrated in Figure 7, to demonstrate the complete three-dimensional conjugacy which is intrinsic to the wavefront reconstruction process.

If a collimated coherent light beam impinges upon the hologram the effect is as though the previously "arrested" electromagnetic field had been released—permitted to continue propagation without modification to indicate that an interruption had occurred. Significantly, it follows then that no difference exists between viewing the original ob-
ject field and the reconstructed image field.

Uniquely, this virtual image space contains conjugate constructs for all object planes, with viewing of different planes requiring the same levels of accommodative and convergence effort attending the viewing of the original object space. Further, the perspective of the scene changes with the viewing position and parallax effects may also be observed. One may literally look around and behind an object in order to see an otherwise occluded object provided that the more distant one had been illuminated when the hologram was made.

The angles at which the diffracted complex wavefronts proceed from any point on the hologram are inversely proportional to the fringe separation at that location. Herein lies the unique complete conjugacy afforded by holography. Relative to the construction of the hologram, it was pointed out that the fringe spacing was inversely proportional to the angle $\alpha$ between reference and signal bearing beams (Figures 2a and 2b): in the image reconstruction the diffracted angle is inversely proportional to the fringe spacing. Through this double inverse relationship, the object's spatial integrity is preserved.

Amplitude, originally recorded in the hologram as fringe contrast, is retrieved as local variations in amplitude of the diffracted wave which, in turn, is viewed or imaged as local variations in image intensity.

Fig. 8.
Figure 8 is an image reconstruction from the hologram depicted in Figure 6.

As indicated in Figure 7, a second set of wavefronts proceed from the illuminated hologram to produce a real aerial image that may be recorded on film. The convergent wavefronts responsible for this complete image space are produced by the Fresnel zone plate property of the hologram fringe pattern of each object point.

It should be noted that it has not been necessary to employ an image forming lens system, with its intrinsic limitations on image quality, either in the formation of the hologram, or for the viewing and recording of image space.

An interesting property of the hologram is its ability to store the "images" of many different object spaces on a single film. Reconstruction and viewing of each image, separately, may be accomplished without distraction from the other recorded information.

In the construction of the hologram, as described, the resolving power of the film limits the resolution of the reconstructed image. It is possible, however, to circumvent this restriction by using a reference beam whose vergence is such that it originates (optically) in the same plane occupied by the object. This advantage is, however, achieved at the expense of field extent. A detailed analysis of the role of film resolution in holography has been made by vanLigten.³

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**Fig. 9.**
APPLICATION

Holography offers the vision investigator the opportunity to present a test or training environment that possesses every attribute of real three-dimensional object space. This presentation may be accomplished without the need of stereoscopic or polarizing aids with their unpredictable artifactual influence. Further, a property of the hologram permits the continuous modification of apparent object distance through change in vergence of the coherent illuminating beam. The viewer must effect appropriate accommodative and convergence levels in order to follow the change in object distance.

In practice, the viewer would be required to look through the hologram. While the fringe pattern offers little or no distraction, it may be reduced essentially to a clear glass plate, with no loss of information, by bleaching the silver opacities of the film.

Figure 9 is a schematic diagram of a holographic fundus camera with which a hologram, Figure 10, of a model eye was made. A re-
corded image reconstruction of the "fundus" is depicted in Figure 11. (The relatively poor reconstructed detail is due to the deteriorated state of the wet model eye employed.)

Significantly, the wavefront reconstruction results in an image continuum from cornea to fundus affording many of those advantages associated with the viewing of the eye itself. Any plane may be focused for specific inspection and, further, magnification of the image may be varied by modification of the illuminating beam's vergence.

Utilizing the enormous data storage capacity of the hologram it is feasible to record various regions of the fundus on a single film through multiple superimposed exposures. Viewing of a specific field may then be accomplished by appropriately orienting the hologram.

In the image viewing and recording technics described earlier, two channels of information, phase and amplitude, are retrieved from the hologram exactly as this information radiated from the original object. As discussed earlier, both the recording film and the retina are insensitive to phase, and therefore only one channel is utilized.

The detection of the second information channel—phase, offers an investigative dimension, untapped by the technic described earlier (Figure 7). To convert this information into readily detectable amplitude modulation, reference beam A (Figure 12), split off from co-
herent source S, is recombined with beam B which has passed through the hologram. The same physical phenomenon of interference, responsible for the formation of the hologram, is operative in producing a fringe pattern which is superimposed over the real and virtual diffracted images due to "illuminating" beam B alone.

This interferometrically formed fringe pattern is a manifestation of path length differences. The curvature of the fundus, which functions as a diffuse secondary source, is responsible for each "point source" lying at a different distance relative to a reference viewing or recording plane. When the light reaching that plane is recombined with reference beam A, the optical path length differences, manifesting relative phase differences in that plane, interfere constructively and destructively to produce a fringe pattern characteristic of the contour of the fundus. Performing interferometry upon the hologram of the model eye has enabled the authors to view a fringe pattern which is characteristic of
the contour of the "fundus." In the living eye other possible path length differences may arise from inhomogeneities of index in corneal, lenticular, or vitreous bodies.

The precise relative determination of fundus curvature may afford a sensitive means of detecting pathologically induced departures or discontinuities in fundus contour. The detection of localized lenticular changes, probable precursors of cataractous changes, may provide a valuable research technic in the quest for a therapeutic approach.

It is hoped that this paper will serve to stimulate consideration and investigation of the potential which holography holds for the ophthalmic field.

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REFERENCES
