# 16 Holography

## INTRODUCTION

Holography was invented in 1948 by British (Hungarian born) scientist Dennis Gabor (before invention of lasers). Its success is due to the laser however, and was aided by an important off axis technique introduced by Leith and Upatnieks in 1962.

## 16-1 CONVENTIONAL VERSUS HOLOGRAPHICS PHOTOGRAPHY

A conventional photograph is a 2-D version of a 3-D scene and which brings into focus ‘every part of the scene that falls within the depth of field of the lens. A photograph lacks depth perception or parallax (associated with a real scene). The **hologram (Greek for “whole message”)** succeeds in effectively “freezing” and **preserving for later observation the intricate waveform of light that carries all the visual information of the scene.** In viewing a hologram, this wavefront is reconstructed or released, and a viewer sees what would have been seen if present at the original scene through the “window” defined by the hologram. **The reconstructed waveform provides depth perception and parallax, allowing a viewer to look around the edge of any an object and see behind it.**

The **realistic qualities** of a holographic image stems from the **preservation of information** relating to **both** the **phase and amplitude (irradiance) of the wavefront**. Devices like photographs and photomulipliers are sensitive to only radiant energy received and consequently do not record the phase relationships of waves arriving from different directions and distances. **To record phase relationships it is necessary to convert phase information into amplitude information**. This can be done **using the interference of light** (recall that in phase light constructively interferes and out of phase light destructively interferes). If a **wavefront from a scene is made to interfere with a coherent reference wavefront,** then, the **resultant interference pattern contains information on the phase relationship of each part of the original wavefront** with reference wave and thus with every other part. This process is often described as carrier wave (reference wave) that is modulated by the signal wave of the scene.

In **conventional photography we say that a one-to-one correspondence exists between the object and imag**e (i.e., all the light from a single point of a scene is focused to a single point in the image). By contrast a hologram is made without a lens or other focusing device and is a complex interference pattern of microscopically spaced fringes and not an image. **Each point of hologram receives light from every point of the scene (i.e., every object point illuminates the** entire hologram). **There is no one-to-one correspondence** between the object points and the wavefront before the reconstruction. The **hologram is a record of the entire signal wave**. *If a hologram is cut into pieces, each piece projects the entire image, but as if viewed from a smaller subset of angles*.

## 16-2 HOLOGRAM OF A POINT SOURCE

The most useful starting point in examining holography is with the simplest example possible, the hologram of a point source. In figure 16-1a, a coherent monochromatic plane wave (i.e., the **reference**

**beam**) **and scattered** spherical **wavefronts** (from object point P) **illuminate** a **photographic plate**. The developed plate shows a series of concentric interference rings about X as the center. Point P falls on

such a ring. If the optical path difference (OP – OX), which falls on such a ring, is an integral number of wavelengths, then the reference beam arrives in step with the scattered subject beam (i.e., they constructively interfere). The developed plate is called a Gabor zone plate (or zone lens) which has circular transmitting zones. The Gabor zone plate is called a sinusoidal grating because the optical density and therefore the transmittance varies as $cos^2(ar^2)$ along the radius of the zone pattern (a is a constant of dimension m$^{-2}$. **This sinusoidal plate is a hologram of point O.** See Figure 16-1c

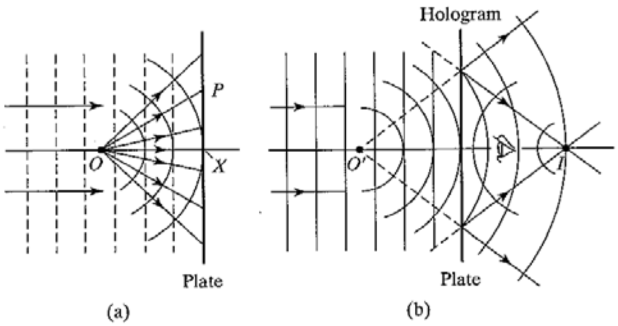

**Figure 16-1** Hologram of a point source $O$ is constructed in (a) and used in (b) to reconstruct the wavefront. Two images are formed in reconstruction.

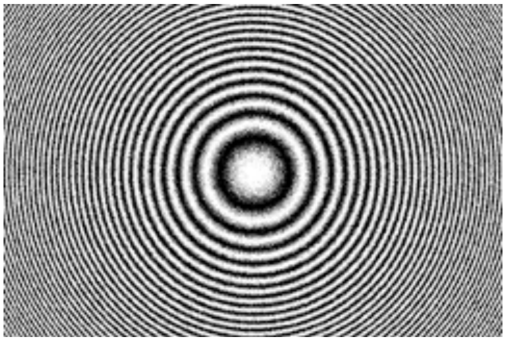

Figure 16-1c Sinusoidal Plate

**The hologram does not resemble the object,** but the object may be reconstructed as in Figure 16-b by placing the hologram back into the reference beam without the presence of the object O. Just as light directed from O interfered with the reference beam to produce the zone rings, now the same beam is reinforced in diffraction along the directions that diverge from the equivalent point **$O'$.** The point thus locates a virtual image of the original point O, seen on reconstruction by looking into the hologram. The condition for reinforcement must also be satisfied by a second point on the exit side of the hologram. The diffracted light thus also, converges to **point I and forms a real image** of the original point O and can be projected on a screen. See Figure 16. For an off axis object at infinity, the zones are straight, parallel interference lines and form **a grating hologram** (this is a **special case of two point-source interference**).

When point object O is replaced by an extended object, or 3-D scene, each point of the scene produces its own Gabor pattern on the plate. **"The hologram is now complex montage of zones in which is coded all the information of the wavefront from the scene".** On reconstruction, each set of zones produce **real and virtual images and the original scene is reproduced**. **One usually views the virtual image** by looking into the hologram. To eliminate the undesirable light from the real image if viewed head on (as in figure 16), **Leith and Upatnieks introduced an off-axis technique using one or more mirrors to bring reference beam in from a different angle so that the real and virtual wavefronts are separated.**

# 16 Holography

The two basic types of holograms are Gabor zone plates (points at finite distance) and holographic grating (points at infinite distance). If the zone plate or grating provides a **square wave type of transmittance multiple diffracted images are possible** (resulting in m$^{th}$ [limited by max diffraction angle] order patterns). The **Fresnel zone plate has this property** but is different from the Gabor zone plate. It can be shown that when the transmittance profile of the grooves or zones is not sharp, but varies continuously, the behavior of higher orders is modified and consequently when the transmittance profiles follow a sinusoidal $cos^2(bx)$ (grating) or $cos^2(ar^2)$ (circular zone plate) irradiance, only the zeroth and first order images appear upon reconstruction. “For the circular zones, the two first order images are the real and virtual images discussed”.

In the holograms shown in Figure 16-1a the sinusoidal irradiance can fall to zero at points of destructive interference when the signal and reference beam are equal in amplitude. **The emulsion is incapable of responding linearly** in all irradiances so that the developed plate will show a distorted $cos^2(ar^2)$ transmittance and **higher order terms will not be suppressed**. **By making the reference beam stronger than the signal beam, the minimum irradiance on the emulsion can be raised to the level of its linear response characteristics.** A variation in the transmittance is produced (i.e., $T = T_0 + T_m cos^2(ar^2)$ ) and **higher order terms are eliminated.** The **compromise** is that since the $cos^2(ar^2)$ transmittance is now superimposed over a non-zero transmittance $T_0$ , **and fringe contrast is reduced.**

As noted above the amplitude of the reference wave is greater that the signal or object wave so that the reference wave is modulated by the signal. **Because of the linear response of the emulsion, the effect of variations in signal strength is to produce variations in contrast of the interference fringes, whereas variations in phase (or direction) produce variations in spacing of the fringes.** “Thus it is in the local variations of fringe contrast and spacing across the hologram that the corresponding variations in amplitude and phase are encoded”.

## 16-2 HOLOGRAM OF AN EXTENDED OBJECT

One holographic technique to produce an off axis reference frame beam modulated (see definition of) by a beam of diffusely reflected light from a 3-D scene is shown in Figure 16-2. The setup is somewhat reminiscent of the Michelson interferometer in that a laser sends out a beam that is split with a beam splitter into a reference beam and a subject beam and after traveling different paths recombine on a photographic plate. The reference beam, $E_R$, is directed by two mirrors onto the plate, while the subject beam is diffusely reflected from the subject onto the plate. These two beams interfere and produce a hologram.

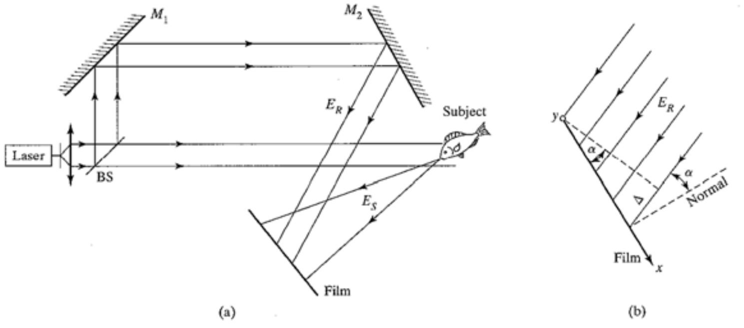

Figure 16-2 (a) Off-axis holographic system. (b) Orientation of film with reference beam in (a).

# 16 Holography

The derivation of the hologram of an extended object is straightforward, elegant and fecund with useful physics concepts. **Below follows an overview of the method.** The reader is directed to **Pedrotti and Pedrotti,** pages 376-378, for a more complete description.

**Reference beam** at plane of film is described by the complex electric field

$$E_R = re^{i(\omega t+\varphi)} \tag{16-1}$$

The reference beam amplitude r = r(x,y) and is assumed constant over the plane wavefront.

**Geometry point:** The phase angle $\varphi$ arises from the angle $\alpha$ between the film plane and the plane wavefront of the reference beam as indicated by figure 16-2b. It can be shown that $\varphi$ relates only to the tilt of the film plane relative to the reference beam and appears as an exponential factor in Eq. (16-1):

$$E_R = re^{i(\omega t)}e^{i\varphi} \tag{16-3}$$

If the reference beam were not present, the film would be illuminated only by the **subject beam**,

$$E_S = se^{i(\omega t+\theta)} \tag{16-4}$$

**where s(x,y) is the amplitude of reflected light at different parts of the film and $\theta$(x,y) is a complicated function due to the variation of phase of the light reaching the film from different parts of the film.**

**The irradiance of the subject beam is proportional to the square of the magnitude of the complex field amplitude $E_s$** and we define the subject beam scaled irradiance $I_s$ as

$$I_s = \ |E_s|^2 = \ E_S^* E_S = \ [s(x,y)] \tag{16-5}$$

which has no information on the phase of the subject beam.

With the reference beam present the resultant amplitude $E_F$ at each point of the film –subject to scalar approximation is given by

$$E_{F=} E_R + E_S$$

So that the scaled irradiance on the film is,

$$I_F = |E_F|^2 = (E_R + E_s)(E_R^* + E_S^*)$$

Multiplying binomials and simplifying yields

$$I_F = r^2 + s^2 + rse^{i(\theta-\varphi)} + rse^{-i(\theta-\varphi)} \tag{16-7}$$

**The scaled irradiance $I_F$ describes the hologram as and is a function of x and y and thus varies from point to point on the film plane (i.e., when the film is developed, its irradiance is determined by $I_F$.**

**Reconstruction of scene:** To reconstruct the scene (minus the subject), the hologram is placed in the reference beam with the same orientation as in the image formation (see Figure 16-b). When illuminated by the reference beam, the hologram (transmittance function) modulates both the amplitude and phase of the beam. The signal is the same as before (Equation 16-1).

The resulting emergent beam can be expressed (except for constants) in terms of the field $E_H$ by

$$E_H \propto I_F\, E_R = (r^2+s^2)E_R + r^2 s e^{i(\omega t+\theta)} + r^2 e^{i(2\varphi)} s e^{i(\omega t-\theta)} \tag{16-9}$$

The three terms can be interpreted as the reconstruction of three distinct beams from the hologram. Each beam is also illustrated in Figure 16-3. The **first term**,

$$E_{H1} = (r^2+s^2)E_R = (r^2+s^2)re^{i(\omega t+\varphi)}) \tag{16-10}$$

**represents** a **reference beam modulated in amplitude but not in phase.** It appears that the incident beam passes through the hologram without deviation (i.e., corresponds to zeroth order diffraction term).

The second term is

$$E_{H2} = r^2 s e^{i(\omega t+\theta)} \tag{16-11}$$

which describes the subject beam, amplitude modulated by the factor $r^2$. This beam represents a reconstructed wavefront from the subject and diverges from the hologram as if coming from a virtual image from behind the hologram. **This virtual image is what is customarily viewed.**

The third term is given by

$$E_{H3} = r^2 e^{i(2\varphi)} s e^{i(\omega t-\theta)} \tag{16-12}$$

and represents the subject beam, modulated in both phase and amplitude. This beam reconstructs the subject beam of Eq. (16-4) but with **phase reversal** (i.e., $e^{i\theta}$ by $e^{-i\theta}$) and every phase delay in $E_s$ shows up as a phase advance. **The image is turned inside out.** Because of the phase reversal, **original diverging rays (e.g., those from $E_{H2}$) which form a virtual image, become converging and form a real image** on the viewing side of the hologram. The factor $e^{i(2\varphi)}$, when compared to the phase term in Eq.(16-23) indicates an angular displacement of the image orientation by $2\alpha$ relative to the normal film plane.

**The off-axis system shown in Figure 16-2 produces a hologram in which the two first orders are separate in direction from each other and the zeroth-order beam.**

The hologram made of an extended object shows the same essential features as the hologram of a point object.

# 16 Holography

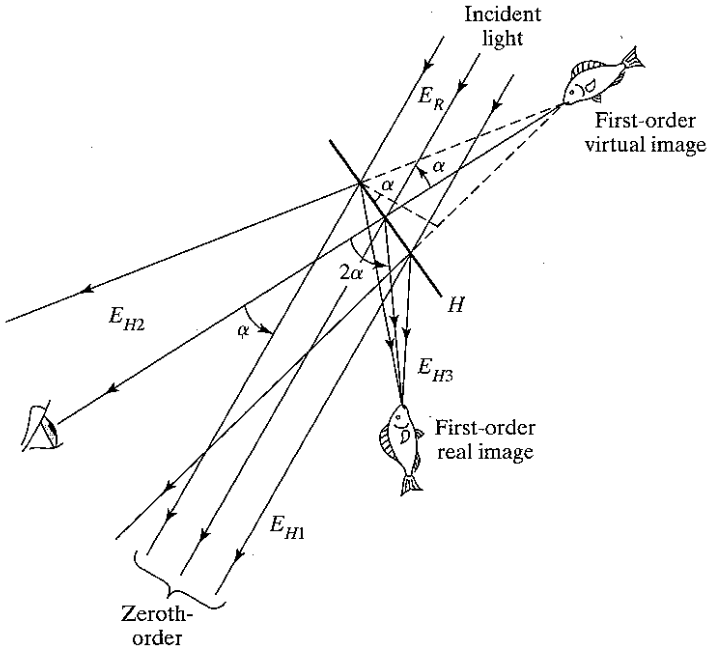

**Figure 16-3** Reconstruction of hologram formed in Figure 16-2a.

## 16-3 HOLOGRAM PROPERTIES

The entire hologram receives light from each object point in the scene and as a result any portion of the hologram contains information of the whole scene. If a hologram is cut up into small squares, each square is a hologram of the whole scene, although the reduction (in aperture) degrades the resolution of the image. The same scene is viewed but with different perspective and is complete, exhibiting both parallax and depth. Another interesting property of a hologram is that a ‘negative’ of a hologram alters neither the fringe contrast nor spacing and hence does not modify the stored information.