Fourier Optics

Appendix B

Holography

Source: “A. Nussbaum and R. A. Phillips, “Contemporary Optics for Scientists and Engineers”

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11

HOLOGRAPHY

11-1 Introduction

The word *hologram* comes from the Greek word *hòlos* meaning the whole. In a hologram the entire wave front including amplitude and phase (which is very important) is recorded. As we have seen previously, phase variations in an object greatly affect its diffraction pattern. In the ordinary photographic process, the film records the intensity I, or E^2, throwing away the phase information. But in the holographic process, the film records both amplitude and phase. When a hologram is properly illuminated, an exact replica of the original wave front is reconstructed. This means that information is recorded in three dimensions in a hologram, as compared to two dimensions by an ordinary photographic camera.

The waves used to record holograms must be spatially and temporally coherent, thus requiring a laser as a source. We shall see that there are many different ways in which holograms are used. One is for information storage devices; a very high density can be stored. Another feature of holograms is that multiple exposures can be made on the same film. When two exposures are made of the same object, the reconstructed waves interfere, and this can be used to detect small changes in the dimension of an object. Holograms are also used in vibration analysis and in contouring.

The hologram is analogous to a modulated carrier wave in communications. When the modulated wave is mixed with a reference wave at the detector, it is demodulated, and this leaves the pure signal. Both the phase and amplitude of the signal are recovered in this process.

We are already familiar with methods that permit recording and display of phase information. In the phase contrast microscope (Chapter 10), variations in the phase of an object are converted into variations of amplitude. This is done by shifting the phase of the carrier (dc term). The general method then of recording phase information is to combine a wave with a uniform coherent reference wave.

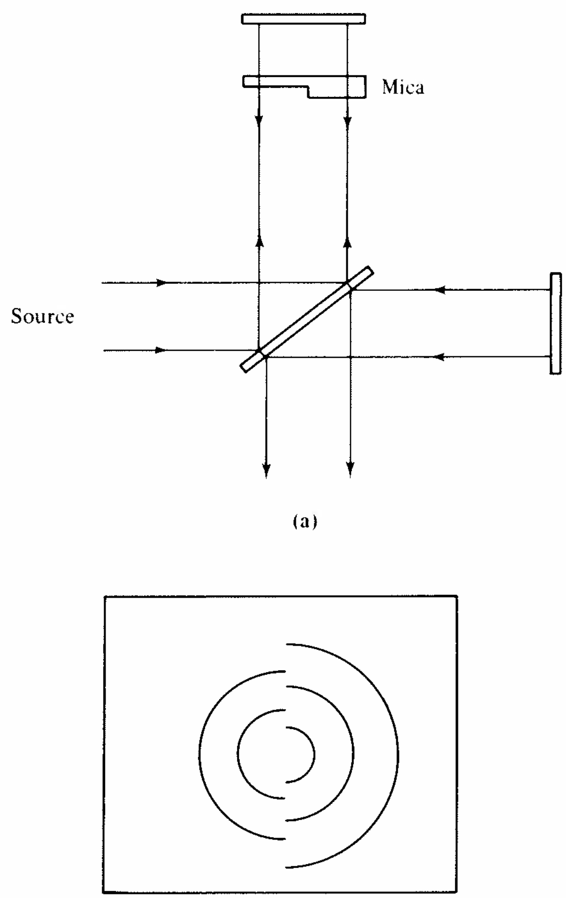


Figure 11-1 A piece of mica with a step in the surface is inserted in one arm of a Michelson interferometer. (a) Phase changes in the wave passing through the step are recorded by combining the wave with a reference wave from the other arm (b).

The procedure will be illustrated by a Michelson interferometer with a piece of mica in one arm. (See Section 7-8.) The mica is assumed to have a step across one surface. Since mica is transparent, it introduces phase variations in the wave passing through it. There will be a discontinuity in the phase of the wave front across the step. These phase variations are recorded when the wave is mixed with the reference wave from the other arm (Fig. 11-1).

11-2 A Plane-Wave Hologram

We will first consider the simplest possible hologram, one produced by recording the interference pattern of two plane waves (Fig. 11-2). One wave is designated the *reference wave* and the other is designated the *object wave*.

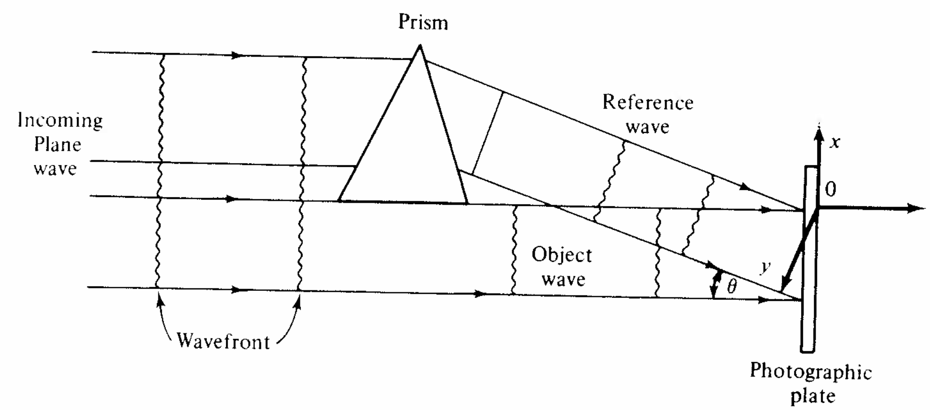


Figure 11-2 The arrangement for recording a hologram. The reference and object are plane waves.

These two plane waves set up a standing wave pattern which is recorded by the photographic plate. The object wave consists of a plane wave propagating in the z direction and is given (Chapter 5) by

$$E = E_1 e^{i(kz-\omega t)} \tag{11-1}$$

The reference wave propagates at an angle θ with respect to the z axis. This wave is described by the propagation vector $\mathbf{k}$, and the factor $\mathbf{k} \cdot \mathbf{r}$ is

$$\mathbf{k} \cdot \mathbf{r} = k_x x + k_z z \tag{11-2}$$

For small values of the angle θ, k_x and k_z are

$$k_x = k \sin\theta \sim k\theta \tag{11-3a}$$

$$k_z = k \cos\theta \sim k \tag{11-3b}$$

The reference wave then is described by

$$E_r = E_0 e^{i(k\theta x + kz - \omega t)} \tag{11-4}$$

and the combined field of the two waves is

$$E_T = E + E_r = e^{i(kz-\omega t)}[E_1 + E_0 e^{ik\theta x}] \tag{11-5}$$

The intensity I is obtained from Eq. (5-15) but we shall ignore the factor of $\frac{1}{2}$ since we are interested only in relative values. Thus

$$\begin{aligned} E_T^2 &= E_1^2 + E_0^2 + E_1 E_0 e^{ik\theta x} + E_1 E_0 e^{-ik\theta x} \\ &= E_1^2 + E_0^2 + 2E_1 E_0 \cos(k\theta x) \end{aligned} \tag{11-6}$$

Next we must consider the photographic process. The density of exposed grains d in the film is given by

$$d = \gamma \log_{10} E_T^2 \tag{11-7}$$

where γ is a characteristic of the film that depends on E_T^2. After the film is developed and illuminated by a uniform plane wave, the transmission is described by the amplitude transmission factor t, related to d through the equation

$$t = 10^{-d/2} \tag{11-8}$$

Substituting the expression for d into Eq. (11-8) yields

$$t = (E_T^2)^{-\gamma/2} \tag{11-9a}$$

or

$$t = [E_0^2 + E_1^2 + 2E_0 E_1 \cos(k\theta x)]^{-\gamma/2} \tag{11-9b}$$

If we assume $E_0^2 \gg E_1^2$, this can be expanded to

$$\begin{aligned} t &= (E_0^2)^{-\gamma/2}\left[1 - \frac{\gamma}{2}\frac{E_1^2}{E_0^2} - \gamma\frac{E_1}{E_0}\cos(k\theta x) + \cdots\right] \\ &= C[E_0^2 - \gamma E_1^2 - 2\gamma E_0 E_1 \cos(k\theta x)] \end{aligned} \tag{11-9c}$$

where C is a constant. If a plane wave of amplitude E_3 illuminates the plate, the transmitted amplitude is given by

$$E_{\text{tran}} = E_3 t \tag{11-10}$$

Assuming that E_0^2 is much greater than E_1^2, Eqs. (11-9c) and (11-10) show that, to within some constant factors, the transmitted wave is identical to the object wave captured on film.

Suppose we illuminate the film by a plane wave and ask. "What does the transmitted wave look like to an observer?" The transmitted wave is simply the diffraction pattern of the hologram. As shown in the previous chapter, the field distribution at a great distance from the film can be obtained by placing the film in front of a lens and looking for the field distribution on the focal plane of the lens. Also, the field distribution across the focal plane is the Fourier transform of the field distribution across the aperture.

The aperture function is

$$\begin{aligned} P(x) &= E_3 t \\ &= a + b\cos(k\theta x) \end{aligned} \tag{11-11}$$

and the transform (Eq. (A-22)) in terms of the spatial frequency $\nu = ku/f$ (Eq. (10-45)) is

$$E(u) = \int_{-\infty}^{\infty} (a + b\cos k\theta x) e^{i\nu x}\, dx \tag{11-12}$$

$$= a\delta(0) + b\delta\left(\theta \pm \frac{u}{f}\right) \tag{11-13}$$

There will be three spots on the focal plane behind the lens. The central one at $u = 0$ (the dc term) represents the undeviated beam. There are two side spots, one at $u = f\theta$ and the other at $u = -f\theta$. Writing the cosine in exponential form, we see that one spot comes from $e^{+ik\theta x}$ and the other from $e^{-ik\theta x}$. These are the first-order diffraction maxima (Fig. 11-3). Note that only the first order is present in the diffraction pattern because there is only one Fourier component in the aperture function. Without the lens, we would have three plane waves leaving the hologram; an undeviated beam ($\theta = 0$) and two beams deviated $\pm\theta$. It is instructive to look at this result employing the terminology of holography; we previously considered it from another point of view in Section 10-9.

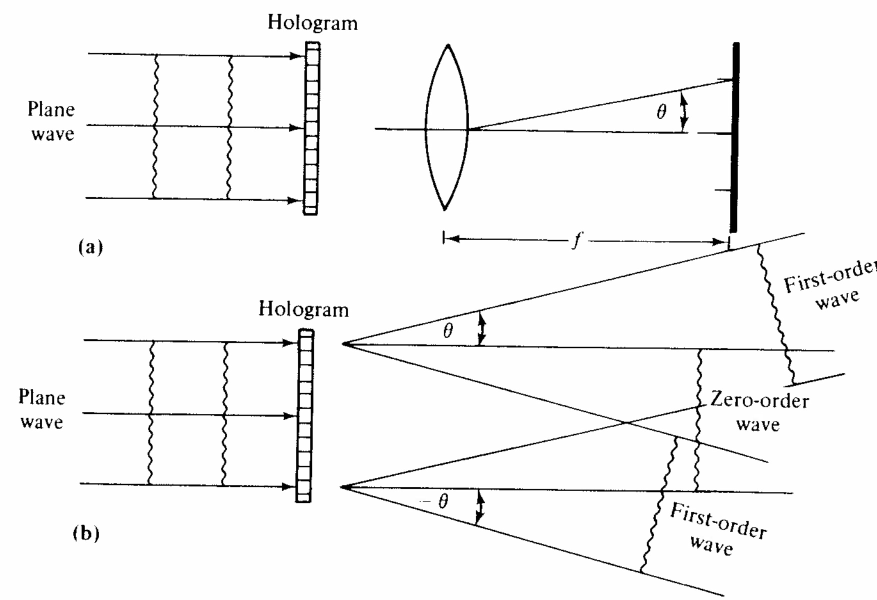


Figure 11-3 The reconstruction of the object wave front.

11-3 A Hologram of a Point Source

Next, let us place a screen having a pinhole in the object beam (Fig. 11-4). Light will be transmitted through the pinhole, so that the effective object will be a point source, and a spherical wave will be generated. The phase of the spherical wave at the center of the photographic plate is taken as kz, and at a distance x from the center of the plate the phase difference is $kx^2/2l$ (Section 10-8).

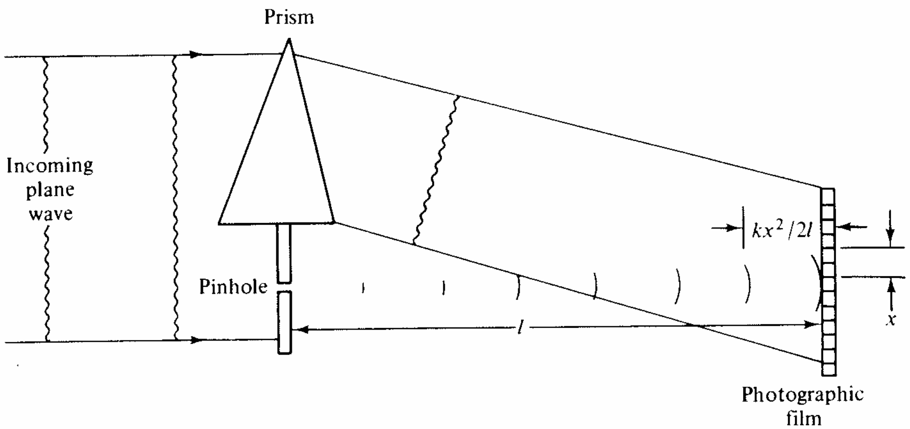


Figure 11-4 The reference wave is a plane wave; the object is a spherical wave.

The object wave is

$$E = E_1 e^{i[(kx^2/2l)+kz-\omega t)} \tag{11-14}$$

and the reference wave, as before, is

$$E_r = E_0 e^{i(k\theta x+kz-\omega t)}$$

The total field E_T is given by

$$E_T = e^{i(kz-\omega t)}[E_0 e^{ik\theta x} + E_1 e^{ikx^2/2l}] \tag{11-15}$$

and the intensity at the film is proportional to E_0^2

$$E_T^2 = E_T E_T^* = E_0^2 + E_1^2 + E_0 E_1 [e^{i[(kx^2/2l)-k\theta x]} + e^{-i[(kx^2/2l)-k\theta x]}] \tag{11-16}$$

When the film is illuminated by a plane wave, the quantity $E_0^2 + E_1^2$ leads to a direct or dc beam (Fig. 11-5). The term $E_0 E_1 \; e^{i[(kx^2/2l)-k\theta x]}$ describes a wave traveling in the $-\theta$ direction, as indicated by the factor $e^{-ik\theta x}$, and it is spherical due to the factor $e^{ikx^2/2l}$. This wave appears to come from behind the plate and is diverging, i.e., identical with the original wave that was captured by the hologram. It therefore produces a virtual image. The term $e^{-i[(kx^2/2l)-k\theta x]}$ represents a wave traveling in the $+\theta$ direction;

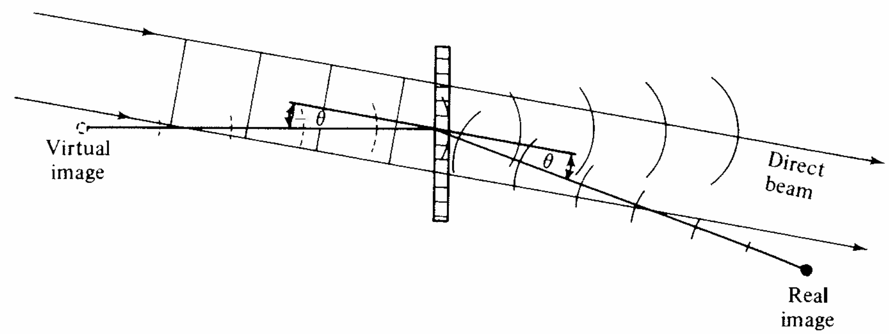


Figure 11-5 When the hologram of Fig. 11-4 is illuminated by the reference wave, three beams are diffracted. In the $-\theta$ direction, there is a virtual image. In the $+\theta$ direction, there is a real image. The direct beam is undeviated by the hologram.

it is a spherical wave converging to a point at a distance l from the plate, and it forms a real image in front of the plate.

Problem 11-1

Plot the phase as a function of x for $f(x) = e^{i[(kx^2/2l)-k\theta x]}$. When a hologram having transmission $t = f(x)$ is illuminated by a plane wave, $E = E_0 e^{ikz}$, the transmitted field is given by $E_T = E_t$. Plot the phase of E_T as a function of x at a given position z. Show that this is identical to the distribution produced by a point source located a distance l behind the hologram and a distance $x' = l\theta$ above the z axis. ■

11-4 A Hologram of a General Object

Any arbitrary object can be represented by a series of points, so that when the object is illuminated, each point on it will become a source. The analysis of a hologram produced by an arbitrary object is a straightforward generalization of the previous analysis for a single point source.

Figure 11-6 shows the arrangement Leith and Upatnieks[11-1] used to record holograms. The object wave is given by

$$E = E(x, y) e^{i[kz-\omega t+\varphi(x,y)]} \tag{11-17}$$

where x and y are the coordinates on the photographic plate. The amplitude information is contained in $E(x, y)$ and the phase information in $\varphi(x, y)$. The reference wave is given by Eq. (11-4). Then

$$E_T^2 = E_0^2 + E^2(x, y) + E_0 E(x, y)[e^{i[k\theta x-\varphi(x,y)]} + e^{-i[k\theta x-\varphi(x,y)]}] \tag{11-18}$$

and the recording on the film is proportional to each of the terms in Eq. (11-18). The developed plate bears no resemblence to the original object;

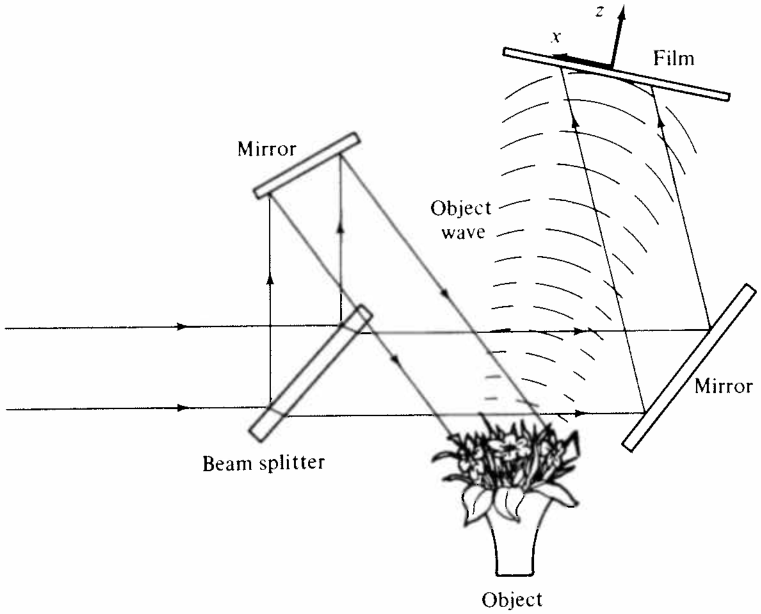


Figure 11-6 Lieth's and Upatnieks' arrangement for recording a hologram.

the interference pattern looks like a jumble of wavy lines. A photomicrograph of a hologram is shown in Fig. 11-7.

Upon reconstruction using the reference wave E_0, we again obtain three waves: the direct wave is $[E_0^2 + E^2(x, y)]$; the wave diffracted in the $-\theta$ direction, $E_0\,E(x, y)\,e^{i\varphi(x,y)}$, forms a virtual image; and the wave diffracted in the $+\theta$ direction, $E_0\,E(x\,y)\,e^{i\varphi(x,y)}$, forms a real image.

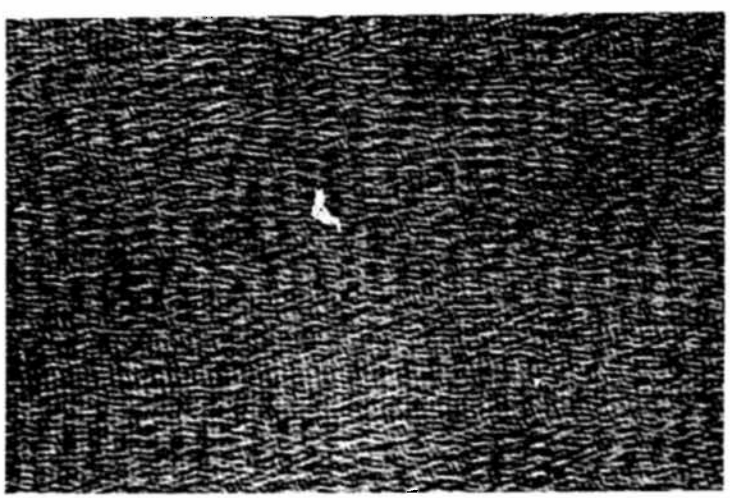


Figure 11-7 Photomicrograph of a hologram.

Earlier we found that the reconstructed wave is an exact copy of the original object wave. As a consequence of this, a hologram records three-dimensional information. Figure 11-8(a) shows the positions of the plate and object during the recording. At point A the object has a different perspective than at point B. In the reconstruction process, when an observer looks through the plate from A (Fig. 11-8(b)), he sees the perspective that

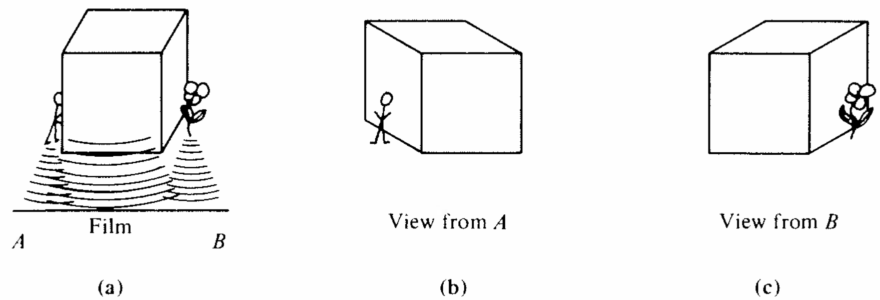


Figure 11-8 Three-dimensional information is recorded on a hologram in (a). The reconstructed wave has one perspective (b) when viewed from the plate at A and another perspective (c) when viewed from the plate at B.

he would have seen originally at A. As he moves his eye to the other end of the plate (Fig. 11-8(c)), he sees a different perspective. In this manner, one can look around corners of a building.

Another striking demonstration that the reconstruction (including phase) is faithful involves a hologram of a scene containing a magnifying lens focused on a scale, for example. When an observer examines the reconstructed image and moves his eye in relation to the holographic plate, he sees different portions of the scale magnified. Furthermore, the reconstructed wave can be photographed with a camera just as if it were the original wave emanating from the object.

Although a laser is needed to record a hologram, it is not required to reconstruct the wave front. A monochromatic source such as a spectral lamp works almost as well as a laser. The difference in the quality of the reconstruction is in the resolution, since edges are slightly rounded when nonlaser light is used.

11-5 Experimental Considerations

Holograms record an interference pattern between two waves, and the three-dimensional effect is most pronounced when a wide field of view is recorded. We shall now calculate the fringe spacing on the hologram, and then use it to determine the resolution requirements for the film. The x component of $\mathbf{k}$ for an oblique wave is given by Eq. (11-3a) as

$$k_x = k \sin \theta$$

and the maxima of the interference pattern occur when (see Eq. (11-6))

$$\cos (kx \sin \theta) = 1$$

or at separations of

$$\Delta x = \frac{\lambda}{\sin \theta} \qquad (11\text{-}19)$$

For $\theta = 30°$ the fringe spacing is 2λ, which sets the requirement on the film resolution since it must handle a pair of lines at this spacing. Only very special, high-resolution films meet this requirement; the two commonly used are Kodak 649F and Afga-Gevaert 128.

High-resolution films have very fine grain and are therefore slow. Using a 20-milliwatt helium-neon laser as a source, typical exposure times for holograms are on the order of seconds. Since an interference pattern is recorded, both the object and reference mirror must be stationary throughout the recording time. Movement of either by a fraction of a wavelength during this time will shift the fringes, making the pattern wash out. Therefore holograms are recorded on specially constructed tables that eliminate vibrations. The tables are massive and often mounted on air cushions for isolation. Stability is usually the most critical requirement in obtaining good quality holograms.

Problem 11-2

A medium-resolution film can resolve up to 150 lines/mm. If the film is used to record a hologram, what is the maximum permissible angle between the reference and object beams? ■

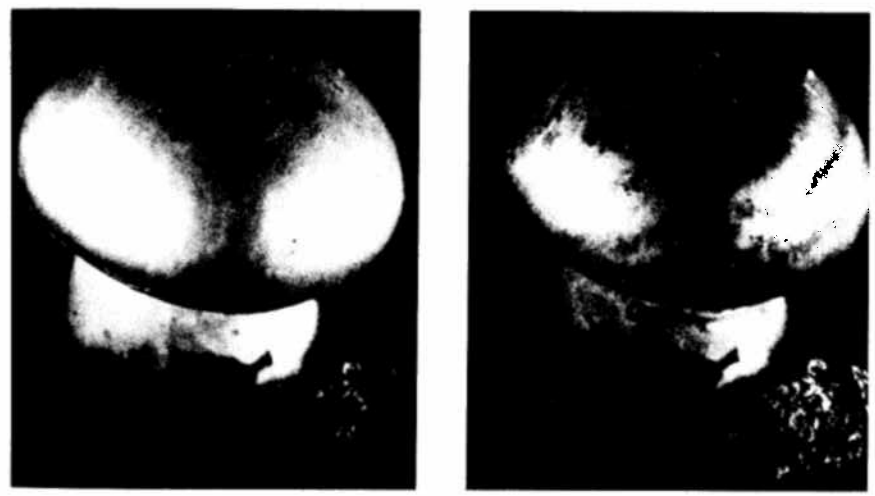
11-6 Four-Dimensional Holograms; Interference Between the Object and the Reconstructed Waves

After recording a hologram as shown in Fig. 11-6, developing the film, and returning it to the original position, an interesting experiment can be performed. The laser is turned on, the reference beam illuminates the plate, and the direct beam illuminates the scene. First, the beam illuminating the scene is blocked off with a card. The reference beam passing through the hologram reconstructs the wave front and a viewer sees a bright scene. Then, the position of the card is changed so that the reference beam is blocked off. The viewer sees the illuminated scene through the plate. If the card alternately blocks off one beam and then the other, the viewer cannot see any difference between the real scene and the faithfully reconstructed one.

This suggests that the direct and reconstructed wave fronts can interfere with each other. If the plate is returned precisely to its original position, the two wave fronts will be in phase everywhere, and any small change in the position or size of the object will produce regions of destructive interference between the two wave fronts. This will appear to the viewer as dark bands superimposed on the object. To observe this interference effect, the film emulsion must be prohibited from shrinking during development and drying, usually by mounting on glass plates.

Another way that holographic interference can be used is by doubly exposing a plate. A hologram of the original scene is made, and the object is given a slight displacement which can arise, for example, from heating, strain, or growth if it is a living object. Then the second hologram is made on the same plate in its original position and is developed. When illuminated by the reference beam, both objects will be reconstructed. Interference fringes will be seen for a displacement of $\lambda/4$ (or odd multiples) between the objects (Fig. 11-9).

An interesting application of the double-exposure idea was developed by T. Jeong and is shown in Fig. 11-10. In this configuration, the cellulose based photographic film is placed in a hollow cylindrical holder and an object is placed inside the cylinder. The output beam from a laser passes through a very short focal length lens which is mounted on the axis of the cylinder (a microscope objective is well suited for this application). The beam comes



(a) (b)

Figure 11-9 Holograms of a growing object. A singly-exposed hologram (a) of a mushroom is shown. A doubly-exposed hologram (b) shows interference fringes superimposed on the plant. A dark fringe can be seen for displacements between exposures which are odd multiples of $\lambda/4$. (*Courtesy of R. Wuerker, TRW Inc.*)

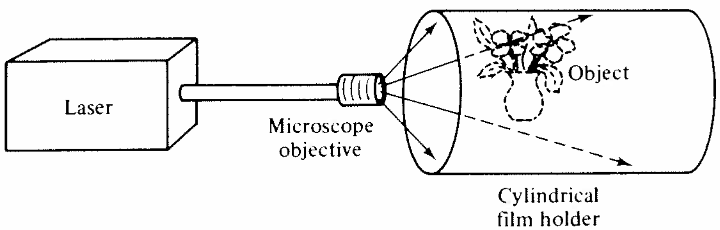


Figure 11-10. An arrangement for recording a hologram having a 360° field of view.

to a point focus and diverges into a cone. The part of the beam which intercepts the film forms the reference beam, while light scattered from the object forms the scene beam. After the hologram has been recorded, the film is reversed, a second object replaces the first, and another hologram is taken on the same film. The object is then removed, the doubly exposed film is developed, and replaced in the holder, and the laser (and hence the reference beam) is then turned on. The laser beam passes through the lens and illuminates the hologram. In one orientation of the film, the first object is seen, and when the film is reversed, the second object is in its place. A particularly interesting feature of this system is that a 360° view of the object is reconstructed: as the cylinder is rotated, each side of the object comes into view.

11-7 Other Applications of Holography

Holograms of several different scenes can be recorded on the same plate. These multiple exposures can be separated if each is recorded with the reference beam oriented at a different angle with respect to the normal to the film. Each reconstructed scene is observed at its own orientation of the plate with respect to the reference beam, and as many as 200 nonoverlapping exposures have been made on one plate.

Holography can also be used to analyze the modes of a vibrating object. Standing waves are set up when a bound object such as the top of a drum vibrates. The standing waves have nodes, that is, positions at which the displacement is zero (see Fig. 5-2). When a hologram is taken of a vibrating object, the nodes and sides of the object are recorded in the usual manner. However, the antinodes have displacements greater than a fraction of a wavelength, and the information on the hologram corresponding to these points is washed out. The reconstructed image of the object has black bands at each of the antinode regions (Fig. 11-11).

In addition, the motion of an object can be frozen by taking the hologram with a pulsed ruby laser instead of a continuously operating laser. A Q-switched ruby laser (see Chapter 15) generates a pulse of light of 10^{-8} second

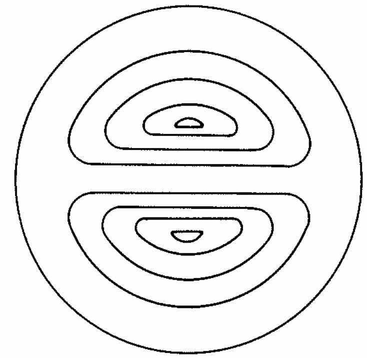


Figure 11-11 The reconstructed image of a vibrating drum head. The dark fringes indicate the position of the antinodes.

duration. During this time, slowly moving objects have very little displacement, and a hologram is recorded of their instantaneous position.

In a particularly interesting application of this idea, Wuerker, Brooks, and Heflinger[11-2] made a hologram of an airborne fruit fly. The reconstructed wave was magnified by a lens. The position of the lens was adjusted until it focused on the fruit fly. The result was a magnified view of a small object in motion. This could not have been accomplished by conventional photography, for a lens must have a short focal length for large magnification and a practical working distance between object and image. A lens with a short focal length has a short depth of field. A flying insect would be impossible to photograph (witness how difficult it is to even catch a fruit fly!). By means of holography and a pulsed laser, a recording with an infinite depth of field was made and the object located and magnified after the fact.

Problem 11-3

A hologram of a moving object is to be recorded on a film having a resolution of 2000 lines/mm using a pulsed ruby laser. The pulse of light emitted by the laser has a duration of 10^{-8} second and wavelength 694.3 nm (6943 Å). What is the maximum velocity toward the film that the object can have? How does this compare to the velocity of a fruit fly? ∎

Problem 11-4

Now consider a point object moving parallel to the film. When the object is 50 cm from the film, the curvature of the wave front arriving at the film will not be very large, and the fringe pattern recorded on the film will be widely spaced. Calculate the spacing if the reference wave is a plane wave incident normal to the film. If the point moves a distance d parallel to the plate, what will be the displacement of the fringe system? How far can the point move in 10^{-8} second without washing out the pattern recorded on the film? Find the maximum velocity parallel to the film. How does it compare to the velocity of a 22-caliber bullet? How would the apparent angular size of the object affect the maximum allowable velocity?

Contouring is another novel application of holography. To contour an object, the laser must operate simultaneously at two wavelengths. λ_1 and λ_2. We will assume that both are in phase when they illuminate the object and when they arrive on the film in the reference beam. Let us consider one point on the object which will be taken at a distance l from a point on the film. If

$$(k_1 - k_2)l = 2\pi m \tag{11-20}$$

where m is an integer, then both waves from the object are in phase on the film, and an interference fringe is formed. When the waves cancel and

$$(k_1 - k_2)l = (2m + 1)\pi \tag{11-21}$$

the fringe has zero visibility.

An actual object has regions of varying distances from the film. Some satisfy Eq. (11-20) and others Eq. (11-21), so that the reconstructed image has bands or contours which correspond to a constant distance. Let us calculate the spacing dl/dm of the contours. Rearranging Eq. (11-20)

$$l = \frac{2\pi m}{k_1 - k_2} = \frac{m}{(1/\lambda_1) - (1/\lambda_2)} \sim \frac{m\lambda^2}{\Delta\lambda} \tag{11-22}$$

where $\lambda_1 \sim \lambda_2 = \lambda$ and $\Delta\lambda = \lambda_2 - \lambda_1$. Differentiating Eq. (11-22) yields

$$\frac{dl}{dm} = \frac{\lambda^2}{\Delta\lambda} \tag{11-23}$$

For a ruby laser ($\lambda = 693.2$ nm) operating in two longitudinal cavity modes 0.1 nm apart, the contoured interval is 5 mm.

Problem 11-5

Could a laser operating at two wavelengths in the visible be used to holographically contour a sheet of mica having a step 20 Å high so that the height of the step could be measured?

Finally we consider color holograms, which are unique because they provide a color image from black and white film. The hologram is recorded at three different wavelengths—usually in the blue, green, and red—and these are sufficient to give a complete color rendition of an object to the human eye. In recording this hologram, the reference beam enters the emulsion from the back of the plate. The reference and object waves create longitudinal standing waves rather than the transverse standing waves across the emulsion previously described. Antinodes are spaced every half wavelength, forming layers of developed grains (Fig. 11-12). When the developed plate

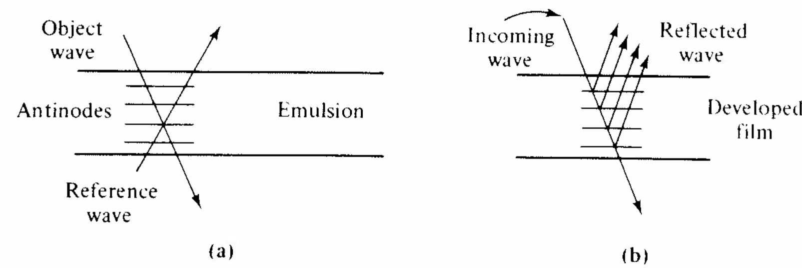


Figure 11-12 In a color hologram longitudinal standing waves are set up in the emulsion (a). When illuminated by white light (b), the developed plate reflects the wavelength corresponding to the one used to make the recording.

is illuminated by white light, those wavelengths that match the spacing of the recorded layers undergo constructive interference and are reflected. With three layers, three color images are reflected.

It should be emphasized that monochromatic light is not required for the reconstruction. Incoherent white light is satisfactory because the hologram selects the wavelength to be reflected out of the continuous spectrum. These holograms can be mounted in frames and hung on the wall like pictures. Although from a distance they look like grey sheets, when a viewer steps up to one that is suitably positioned next to a white light, he sees the scene apparently located deep inside the wall!

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