Fourier Optics

Appendix D

Holograms

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37

HOLOGRAMS

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37–1 Introduction

The basic ideas of holography were originated by Prof. Dennis Gabor[1,2,3] in 1948. With the advent of the laser and an improved process by Leith and Upatnieks,[4,5] it caught the excitement and imagination of the scientific community and has now become an active field of applied research.

Briefly, holography is a process through which a three-dimensional image of an object can be completely recorded on a photographic film or plate without the use of any intermediate imaging devices. For this reason, it is also called lensless photography. The processed photoplate is called a hologram. Some major properties of holograms are the following:

1. The light arriving at the eyes of the observer from an illuminated hologram is precisely the same as that which would come from the original object. Therefore, this three-dimensional image can be photographed from various perspectives or scrutinized by any other ordinary optical means.

2. If a hologram is broken into many pieces, each piece contains a complete view of the entire object. One looks through the hologram as if it were a window behind which the object is situated. If this window is closed, one can peep through a knothole and still see the entire scene but with a more restricted perspective.

3. More than one independent scene can be recorded on the same photoplate. They can be viewed one at a time, without cross interference, by rotating or tilting the finished hologram with respect to the viewing light.

4. Although any hologram can be viewed by a monochromatic point source (not necessarily from a laser), a special kind, called the Lippmann-Bragg hologram,[6,7,8] can be viewed by unfiltered thermal sources such as the sun or tungsten filament lamps.

(1) D. Gabor, *Nature*, **161**, 777 (1948).

(2) D. Gabor, *Proc. Roy. Soc.* (London), **A197**, 454 (1949).

(3) D. Gabor, *Proc. Phys. Soc.* (London), **B64**, 449 (1951).

(4) E. N. Leith and J. Upatnieks, *Sci. Am.*, **212**, 24 (1965).

(5) E. N. Leith and J. Upatnieks, *J. Opt. Soc. Am.*, **52**, 1123 (1962), and **54**, 1295 (1964).

(6) Yu. N. Denisyak, *Soviet Phys.—Doklady*, **7**, 543 (1962).

(7) G. W. Stroke and A. Labeyrie, *Phys. Letters*, **20**, 368 (1966).

(8) L. H. Lin, K. S. Pennington, G. W. Stroke, and A. Labeyrie, *Bell System Tech. J.*, **45**, 659 (1966).

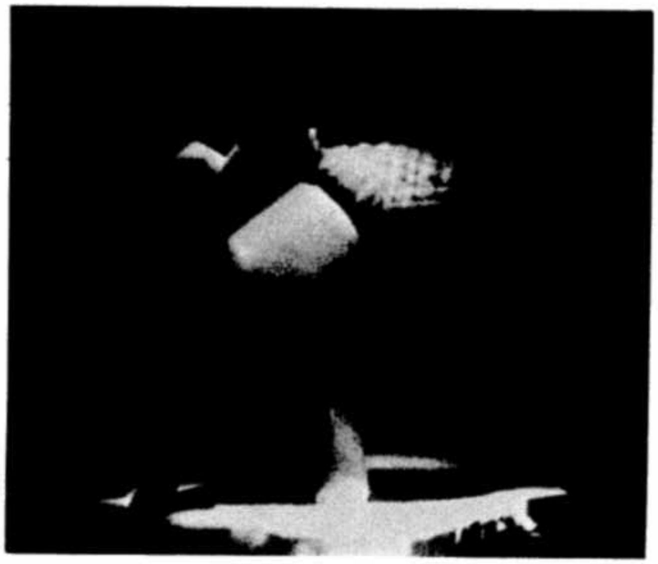

Fig. 37–1

Fig. 37–2

5. A cylindrical hologram can be made which offers a 360-deg view[9,10] of an object; i.e., the observer can walk around the hologram and see the entire object from its front, sides, or back. Turning the cylinder upside down reveals a completely independent scene, also in all perspectives. See the camel in Figs. 37–1, 37–2, and 37–3 and the die in Figs. 37–4, 37–5, and 37–6.

6. They can be encoded so that only the person in possession of a decoding device can see the true image.[11]

7. Three-dimensional multi-color scenes can be recorded and reconstructed holographically.[8,12]

Because of these and many other dramatic characteristics, various possible applications of holography in science and industry can be foreseen. However, the basic aim of this chapter is to present holography as an effective motivational device for students. Since it involves many basic principles in physics and mathematics, an instructor, having the enthusiasm of his students, can guide them to learn a great deal.

Fig. 37–3

A rigorous and comprehensive treatment[13] on this topic is out of the present scope. What specifically will be presented is a guide for teachers for using a particular approach to demonstrate the basic theory of holography and some practical hints for student projects.

[9] T. H. Jeong, P. Rudolf, and A. Luckett, *J. Opt. Soc. Am.*, **56**, 1263 (1966).

[10] T. H. Jeong, Paper presented at April, 1967, Meeting of American Optical Society at Columbus, Ohio.

[11] H. Kogelnik, *Bell System Tech. J.*, **44**, 2451 (1965).

[12] A. A. Friesem and R. J. Fedorowicz, *App. Opt.*, **6**, 529 (1967).

[13] G. W. Stroke, *An Introduction to Coherent Optics and Holography* (Academic Press, New York, 1966).

37–2 Mathematical Background

Initially, students will need to be reminded of the principle of superposition; i.e., in a linear system (a system which obeys Hooke's law), any complex periodic wave can be constructed by taking the sum of pure sine waves of definite frequencies, amplitudes, and phase relationships.

Consider the sine wave of Fig. 37–7a. Its frequency spectrum (also called a Fourier spectrum), as shown in Fig. 37–7b, consists of a zero frequency ("dc") component of amplitude $A(f_0) = 1$, and a single sine function of amplitude $A(f_1) = 1$. In other words,

$$f(x) = 1 + \sin(2\pi f_1 x).$$

Next, consider Figs. 37–8a and 37–8b. These represent a "beat note" which is obtained by adding two sine waves of different frequencies. If the curve $f(x)$ is not symmetrical with respect to the horizontal axis, it merely means that there is a "dc" component $A(f_0)$. Analytically,

$$f(x) = A(f_0) + A(f_1)\sin(2\pi f_1 x) + A(f_2)\sin(2\pi f_2 x).$$

It can be shown that the square wave of Fig. 37–9a can be obtained by summing all the sine waves designated in the Fourier spectrum (Fig. 37–9b). The instructor can actually draw a few of the sine waves on the chalkboard and add the amplitudes together point by point to prove this. The dotted line of Fig. 37–9a is the center of symmetry of the wave, and its amplitude is represented in Fig. 37–9b as the "dc" component. The f_0 component is the "fundamental" of $f(x)$, $3f_0$ is the third "harmonic" (or third order), etc. For a regular square wave, only odd harmonics are present. The dotted line on Fig. 37–9b is the envelope of the spectrum which depends on the ratio between the widths of the top and the bottom of a cycle.

The process of finding the frequency spectrum of a given complex wave is called Fourier analysis, and the corresponding process of finding the complex wave from a given set of sine and/or cosine waves is called Fourier synthesis. To attain a rigorous understanding of holography, detailed knowledge of this branch of mathematics is required. However, for beginning students, it suffices to understand what has been presented above.

For more advanced students, the spectrum of a single pulse can be discussed. This can be considered as a periodic wave with an infinite period. The spectrum consists of a continuous distribution of frequencies; $f(x)$ is a Fourier integral summing all frequencies of given amplitudes and phases, i.e., $f(x)$ is a Fourier transform of $A(f)$.

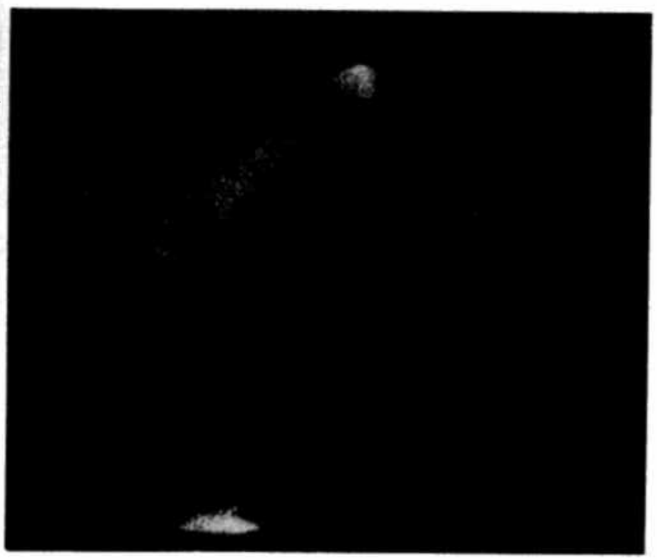

Fig. 37–4

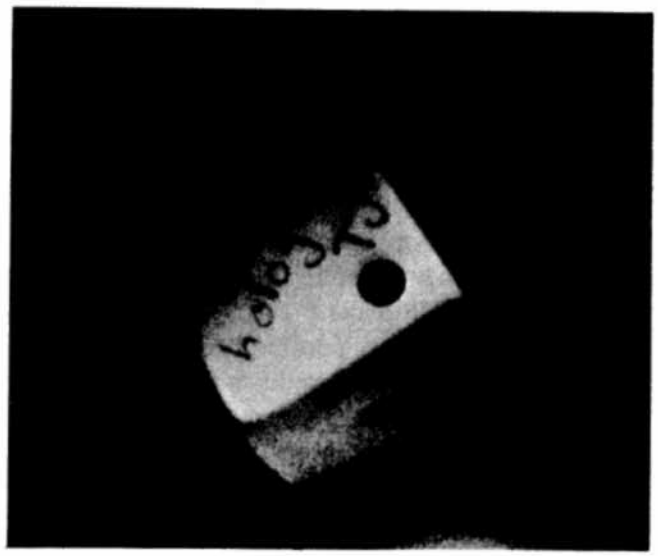

Fig. 37–5

37–3 Physical Demonstration

Having provided the above background, a physical demonstration can now begin. The material involved consists of a sine grating, a "beat" grating, an alternating bar replica grating, a Gabor zone plate, and a hologram of a three-dimensional scene.[14]

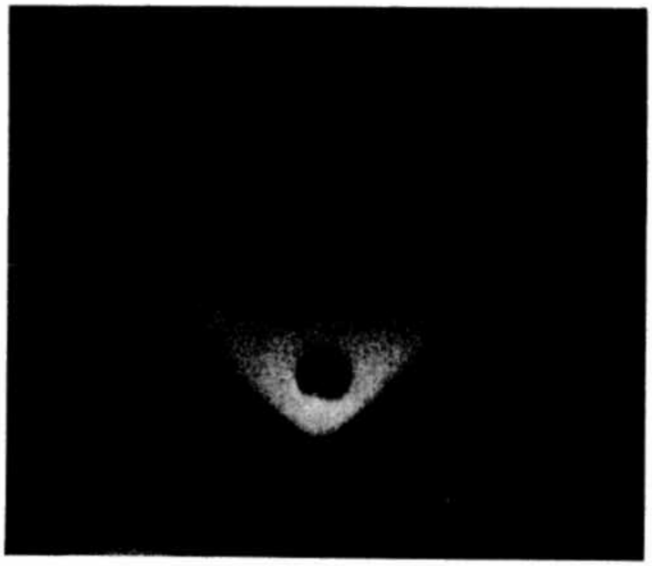

Fig. 37–6

37–3.1 The Sine Grating

The arrangement shown in Fig. 37–10a is used to make the sine grating. A laser beam is split into two components and then recombined at an angle θ to one another on a sheet of photographic film or plate. The intensity of the interference pattern across the plate has a sinusoidal distribution, essentially the same as that caused by a Lloyd mirror or a Fresnel biprism. The spatial frequency increases with the angle θ between the beams according to $f = \sin\theta/\lambda$, where λ is the wavelength of the light. If the laser beam were split into three components, and the third component recombined with the first two, as shown by the dotted line in Fig. 37–10a, the interference pattern would not be significantly changed. Since the film does not "know" whether this component is present or not, the diffraction pattern from it has a symmetrical order on each side. (If the emulsion is thick, the situation will be different. This point will be discussed later.) One is called the complex conjugate of the other. This sine grating can be said to be a hologram of a parallel beam of light, or of a point object located at infinity, since the reconstructed wavefronts are the same as those used to expose the plate.

The basic principle illustrated is that the Fraunhofer diffraction pattern represents the Fourier analysis of the diffracting aperture, in our case a grating or a hologram. If we plot the transmittance (fraction of light energy transmitted) versus distance across the sine grating, the curve would look like Fig. 37–7a, a pure sine wave having a certain number of cycles per millimeter (spatial frequency). As discussed above, such a wave has only one Fourier component, plus a "dc" term. When a beam of parallel and monochromatic light is diffracted by this grating, it can be seen that the diffraction pattern consists of an undeviated beam (the "dc" component) plus one order of diffraction on each side (Fig. 37–10b).

37–3.2 The Beat Grating

The diffraction pattern from a beat grating further demonstrates this principle. The transmittance curve in this case is represented by Fig. 37–8a. As expected, the diffraction pattern of this grating consists of two beams on each side of the "dc" beam, represented by Fig. 37–8b. The beat grating is made in the same manner as the sine grating, with the addition of another object beam from a different angle. The pattern on the grating is just a superposition of two sine gratings of different frequencies. If more than two object beams are used, the beat pattern on the film gets more complex and the diffraction pattern from it merely reconstructs all the object beams. Furthermore, the object beams do not have to be in the same plane.

In the foregoing description, the film is performing a Fourier synthesis while being exposed, i.e., it adds together the individual sine waves caused by the interference between the reference and the object beam(s). The result is a complex periodic wave pattern. When monochromatic parallel light is incident on the processed film, Fourier analysis

[14] This entire package, including a 360-deg hologram, is being distributed by the Welch Scientific Company.

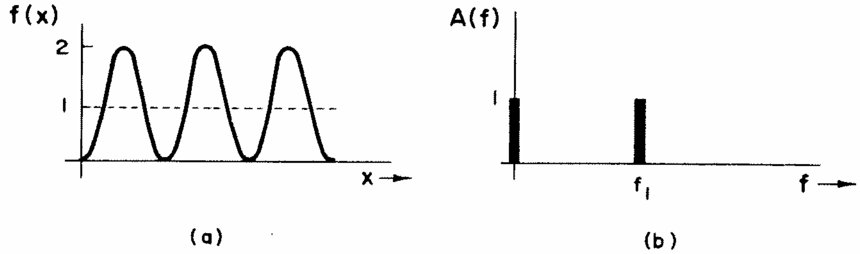

Fig. 37–7

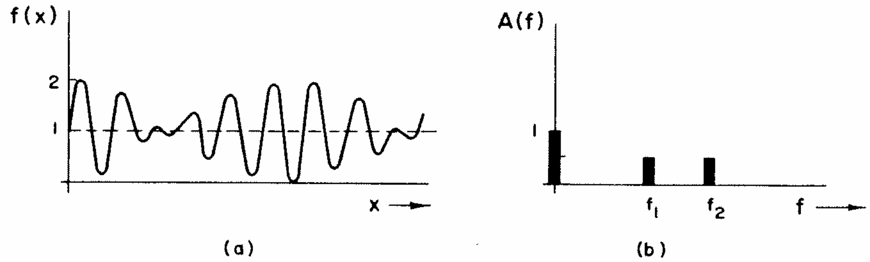

Fig. 37–8

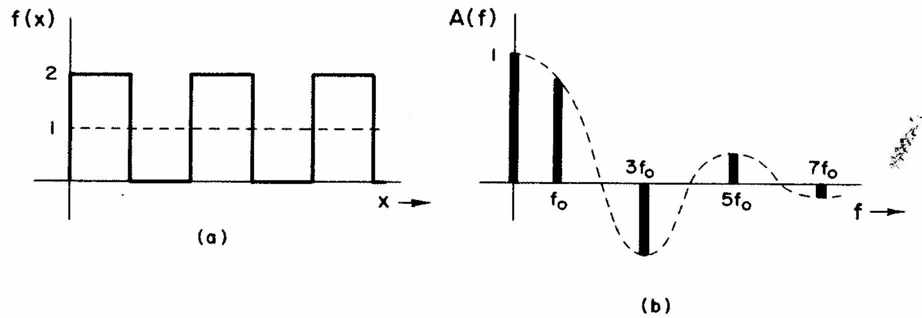

Fig. 37–9

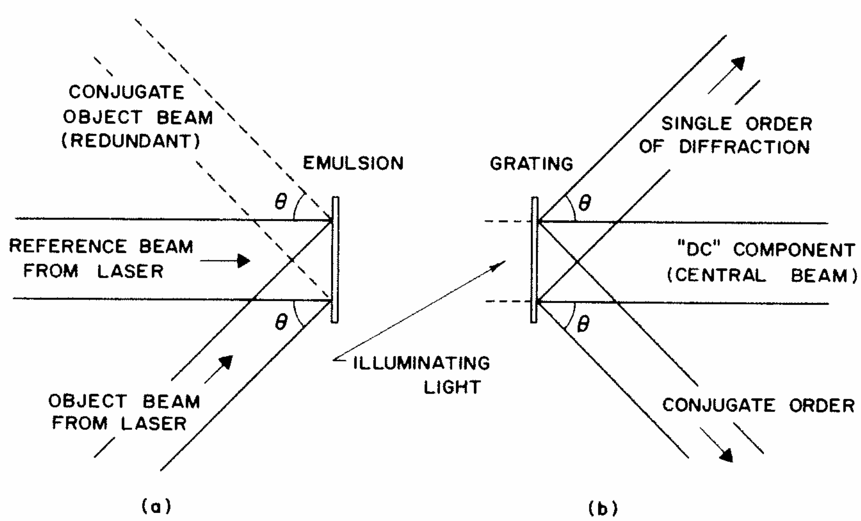

Fig. 37–10

takes place and the light is spread into a configuration similar to that used to make the exposure. This is the process of wavefront reconstruction.

Technically, one can say that the hologram is the Fourier transform of an object function; the diffraction pattern of the hologram is the Fourier transform of the grating function; therefore, the diffraction pattern from the hologram is the Fourier transform of the Fourier transform of the object function, i.e., the object. However, this is more easily said than understood and care should be exercised by the instructor so that the students do not merely substitute this statement for understanding.

37–3.3 The Standard Diffraction Grating

It follows that if a square wave intensity pattern (alternating opaque and transparent bars) is desired on the film, one *could* obtain it by bringing together many object beams of correct amplitudes from predetermined angles. This is not done because there are easier ways of making such a grating. The familiar diffraction pattern, then, shows the spectrum of this wave. Thus, such a grating can be said to be a hologram of many point objects at infinity. It should also be realized now that, in principle, we can make a grating whose diffraction patterns looks like anything we wish.

So far we have concentrated only on point objects at infinity (parallel beams). The same ideas hold when the objects are near the film (divergent beams).

37–3.4 The Gabor Zone Plate

For simplicity, consider the interference pattern formed on the film by using the configuration shown in Fig. 37–11a. Here, the object beam of Fig. 37–7a has traversed a lens and focused at a point. This is equivalent to having light coming from a point object nearby. Notice that the angle, and therefore the spatial frequency, is dependent on the location on the film. For example, the spatial frequency on top of the film (Fig. 37–11a) is $f_1 = \sin\theta_1/\lambda$ and gradually decreases to $f_2 = \sin\theta_2/\lambda$ at the bottom. Thus, the pattern subtends a finite bandwidth.

Imagine for a moment that the film is an infinite vertical plane, the light from the point object is isotropic, and the plane reference wave covers the entire film. Then there is cylindrical symmetry about a horizontal axis drawn through the point object (dotted line, Fig. 37–11a). The diffraction pattern on the film would be an infinite set of concentric rings, centered on the axis, and whose radial spatial frequency increases with the radius. Since our actual film subtends a small off-axis section, the actual pattern formed on it is an off-axis section of the above set. If these rings were an alternatingly opaque and transparent set, they would form an ordinary Fresnel zone plate. However, this set is sinusoidal in character, and it will be given the name Gabor zone plate.

The reconstructed wavefront from this plate is shown in Fig. 37–11b. One way to explain this pattern is as follows: Consider an area on the film small in dimension compared to the distance from

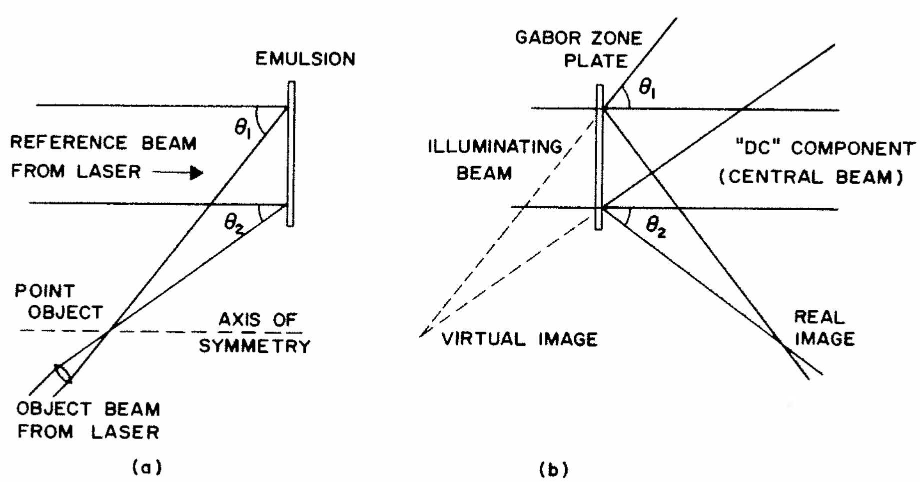

Fig. 37–11

it to the object point. During the exposure, both the reference beam and an element of the object beam arriving at this area can be considered to be parallel. Thus, *locally*, the interference pattern on the film is a pure sine wave. In the reconstruction, light impinging on any part of the processed film will have only one order of diffraction. However, the higher frequency regions have a larger dispersion, diffracting light to a larger angle. Therefore, light diffracted off the top of this grating diverges more than that diffracted from the bottom of the grating. By cylindrical symmetry, half of the diffracted light will converge to a point, forming a real image of the original point, while the other half diverges and forms a virtual image of the same point.

Photographically, an object can be considered as a set of point sources of light located at various distances from the film. If a three-dimensional figurine is substituted for the point object and illuminated by laser light, each point on it will reflect light onto the film and form a system of rings described above. The film would add together, or integrate, all the sets formed by each point on the object, i.e., the interference pattern formed is the superposition of all individual sets. In the reconstruction, each set of rings forms a real and virtual image of a point, thus creating in total a real and virtual image of the entire object.

The simplest possible arrangement to use in making a hologram of a three-dimensional object is shown in Fig. 37–12. Light from a laser is diverged

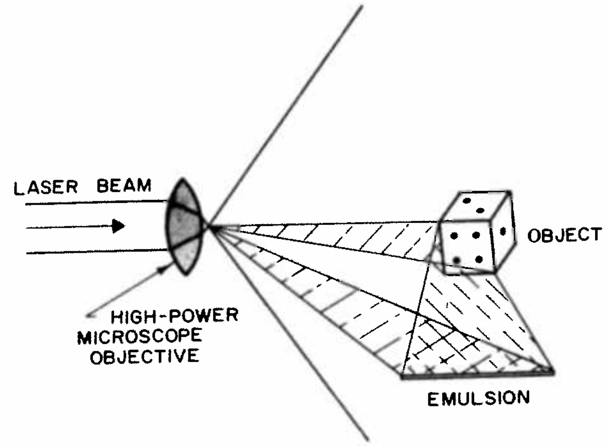

Fig. 37–12

by a lens; part of the light intersects the film directly and serves as the reference beam while the other parts illuminate the object. Light scattered from each point on the object will form with the reference beam a set of Gabor zones on the film. By facing the film directly toward the object rather than toward the reference beam, the virtual image is much easier to observe during the reconstruction.

By taking a figure of revolution of Fig. 37–12, using the original laser beam as the axis, a geometry exists with which a cylindrical hologram described in Section 37–1 (5) can be made.

37–3.5 The Hologram

At this point, an actual hologram of a three-dimensional scene can be shown.

37–4 Relationship Between Holography and Radio

For those who are familiar with radio theory, it should be realized at this time that it is strikingly similar to the theory of holography. Although radio is a time-dependent wave phenomenon and holography is space-dependent, both are described by the same communication theory. The almost trivial mathematical difference between the two is that one operates in the time domain (having t as a variable) while the other operates in the space domain (having $r(x,y,z)$ as a variable) of the Fourier transform theory.

To illustrate this point, let us enumerate some phenomena exhibited in radio and relate them one by one to holography.

37–4.1 Bandwidth

As described previously, a hologram has in general a continuous range of spatial frequencies. The bandwidth of the arrangement shown in Fig. 37–11a is $\sin\theta_2/\lambda < f < \sin\theta_1/\lambda$. For a three-dimensional object, the bandwidth depends on the extreme angles between the references beam and the rays from various parts of the object as they intersect

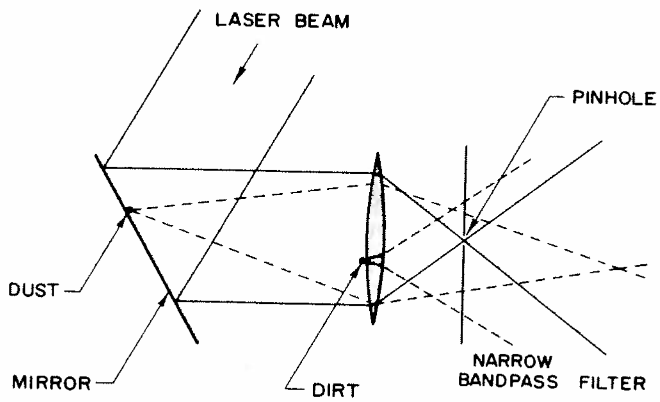

Fig. 37–13

on the film. Therefore, for a given reference beam direction, the bandwidth of the system increases with the physical dimensions and the proximity of the object and the film.

37–4.2 Noise

Static in radio is well known. The spatial equivalence is the smudgy appearance, the whirls and rings that can be seen on a hologram surface which have no relation to the pertinent information recorded. They are caused by the diffraction of dust particles and dirty spots on mirrors or lenses used in making the hologram.

37–4.3 Filtering

A narrow bandpass filter can be used in radio to eliminate the noise in the carrier. Similarly, this can be done in holography. Consider Fig. 37–13. A parallel laser beam is reflected by a dirty mirror and then focused through a dirty lens. The unscattered beam converges to a point of typically a few microns in diameter at the focal plane. The images of the dust particles, however, will occur at the conjugate foci, not coincident with the focal point. Therefore, a simple pinhole[15] located at the focal point will selectively pass the original parallel beam and stop the noise.

A meaningful demonstration on dark field illumination in microscopes can be done using the simple arrangement shown in Fig. 37–14. In this case, instead of the narrow bandpass filter described above,

[15] T. H. Jeong, *Am. J. Phys.*, **35**, No. 5 (1967).

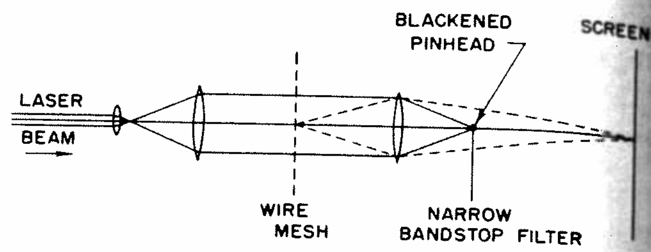

Fig. 37–14

a narrow bandstop filter, i.e., a small blackened pinhead is used. The laser beam is first diverged by a microscope objective and rendered parallel again with a larger lens. The object (a fine wire mesh, for example) is placed in the larger beam. The next lens converges the undiffracted "dc" beam into a point, which is blocked out by the pinhead. The diffracted light, however, is focused at the screen, placed at the conjugate focal plane to the object. An image of the object will then be seen without the bright direct light. By carefully moving the pin along the optical axis of the system, phase reversal can be seen as various orders of diffraction are cut off.

37–4.4 Fidelity

The amplifier and speaker system in radio is considered "Hi-Fi" if it has a wide passband without distortion. This is also true in optics. A larger lens has better resolution (fidelity) than a small one because it gathers a larger number of orders of diffraction (more harmonics) from the object and recombines them at the focal point. The lower limit of resolution is realized when the aperture is so small that only the "dc" component, which carries no information, gets through. The lens here is performing a Fourier synthesis and a Fourier analysis all at once.

The size of the hologram, then, determines to a great extent the ultimate resolution of the image. Although every piece of a hologram gives a complete view of the object, the resolution decreases with the decrease in dimension of the piece—because the bandwidth is being narrowed. When a piece is small enough, only the "dc" component can come through. This point can be demonstrated by directly covering a hologram with a black card with various sizes of holes in it and observing the image through the individual holes.

37–4.5 Encoding

A radio message can be "scrambled" by giving an auxiliary modulation to the carrier. The same can be done to a hologram by inserting a very irregular piece of glass in the path of the reference beam during exposure.[15a] The plane reference wavefront is now warped. In viewing the finished hologram with a plane wave, the image is "scrambled." However, if the same piece of glass is used in the reconstruction, the true image of the object is recovered.

37–4.6 Sideband Suppression and Multiplexing

A sinusoidal carrier has two sidebands. A radio channel can be multiplexed by modulating each sideband independently. How this can take place in holography will be explained in two steps.

1. Sideband Suppression. Figure 37–15 depicts a more realistic picture of a hologram construction because it shows the emulsion having a finite thickness. For example, Kodak 649-F plates have emulsion thickness of about 16 μ. For simplicity, consider two waves interacting on the emulsion as shown, where the dotted lines indicate the crest of the waves. On the surface a sinusoidal diffraction pattern occurs with antinodes located at lines (into the drawing) where the crests meet. On the plane immediately behind the surface, the same pattern occurs but is slightly shifted upwards. As the waves travel through the emulsion, nodal planes are formed as shown by the heavy diagonal lines. When the emulsion is exposed and processed, these darkened planes behave as venetian blinds and suppress one of the sidebands. The effectiveness of the suppression depends on the emulsion thickness and density after development. If the plane object beam is substituted by a three-dimensional object, and a hologram is made, the real image is suppressed, but not lost. By turning the hologram backward, which reverses the direction of the blinds, the real image can be projected onto a screen, and the virtual image is suppressed. In practice, this can be done easily by illuminating the backward hologram with a *narrow* laser beam. The small spot of the hologram used causes a sacrifice in resolution, but depth of field is gained in the projected image.

[15a] H. Kogelnik, *Bell System Tech. J.*, 44, 2451 (1965).

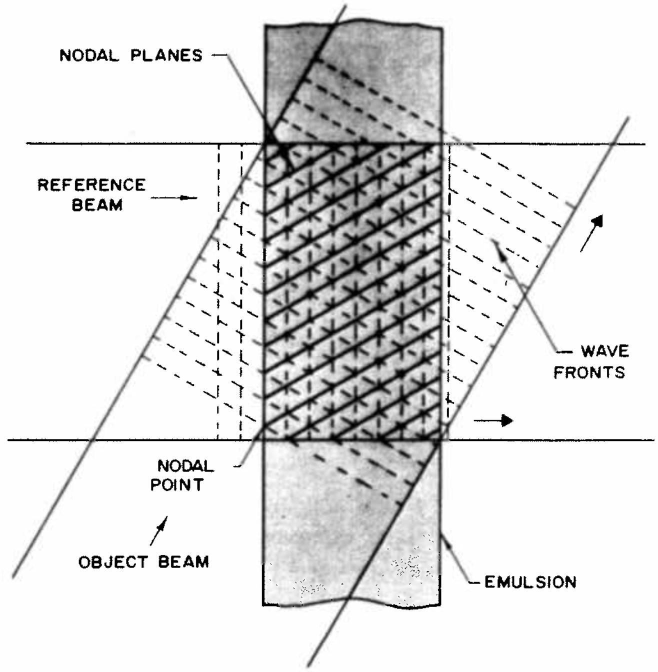

Fig. 37–15

2. Multiplexing. During construction, the once exposed photoplate can be turned upside down and a different object is used for another exposure. In this way, each sideband is modulated separately and the finished hologram will show two completely unrelated pictures, depending on its orientation with respect to the illumination. To avoid "cross-talk," the angle between the reference beam and the object beam should be sufficiently large, and the physical dimensions of the object should be sufficiently small. (In other words, the frequency domains of the two scenes must not overlap.)

At this point we can utilize the fact that the space domain has three dimensions, whereas the time domain has only one. When one looks out at night through a square mesh wire screen window at a street lamp, one sees a diffraction pattern resembling a cross—there are many orders of diffraction both in the vertical and the horizontal directions. This is so because the screen is a two-dimensional square wave, which has many Fourier components. If the transmittance of the screen had been sinusoidal in both directions, there would be

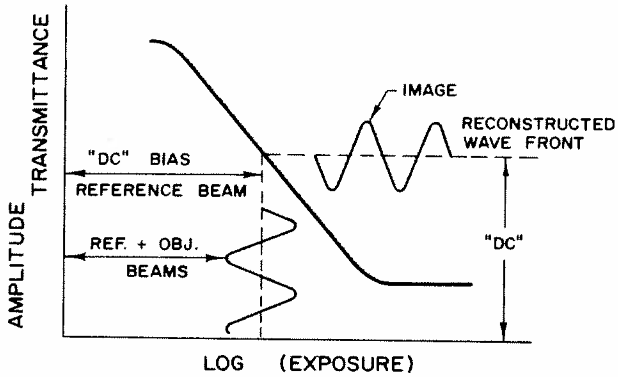

Fig. 37–16

a total of four sidebands, located symmetrically around the lamp. This means that after the initial exposure during a hologram construction, the photoplate can be rotated 90 deg at a time until four completely different scenes, are recorded, one on each sideband. In fact, in principle, any number of independent scenes can be recorded by making a smaller rotation on the photoplate after each exposure, the limit being the over-exposure of the emulsion and the occurrence of cross-talk between adjacent scenes. Over-exposure, however, can be remedied to a degree by bleaching[16] the finished hologram in potassium ferricyanide or mercuric chloride, changing the "amplitude hologram" into a "phase hologram." The latter is similar to a transparent grating having on it a pattern of variations in thickness and/or index of refraction.

37–4.7 Tube Characteristic vs Film Characteristic

Everyone is, to a degree, familiar with the characteristic curve of vacuum tubes and how it affects the transmission of information in radio. A strikingly similar consideration occurs in holography.[17] Figure 37–16 shows the characteristic curve of a typical emulsion. We can consider the reference beam as a "dc bias" which exposes the emulsion uniformly to the center of a linear region of the curve (vertical dotted line) and the object beam as a modulation. For a given emulsion, the total exposure, as well as the ratio between the intensities of the reference and object beams, must be correct in order to transmit the strongest signal without distortion. For Kodak 649-F, the correct intensity ratio between the reference and the object beams is 7.5.[17] The exposure, of course, depends further on the total intensity at the plane of the photoplate. In practice, before exposure, the plate can be substituted by a white card. The brightness as judged by eye caused by the reference beam alone should be approximately twice that caused by the total scattered light from the object. Since the response of the eye is logarithmic, this gives a ratio of ten to one.

We have already mentioned that because of the additional dimensions available in the space domain, there are events in holography which cannot be related to radio directly. Examples so far given are the existence of more than two sidebands and the 360 deg hologram. There is still another class of holograms which utilizes the fact that the emulsion has a finite thickness. This is the white light reflection hologram, also called the Lippmann-Bragg hologram.

Referring back to Fig. 37–15, we note that the nodal planes formed become more parallel to the plane of the photoplate as the object beam is made more parallel to the reference beam. To the limit that both beams incident normally on the plate, the nodal planes would be parallel to the plate (standing waves). Because the emulsion is many microns thick, whereas the visible light has wavelengths around ½ μ, many planes are formed into the emulsion (assuming that we are not limited by the grain size of the emulsion). Precisely the same effect occurs if the reference and object beams impinge on the photoplate from opposite sides, which is experimentally more easily arranged.[17a] This hologram then behaves precisely as a crystal, and produces Bragg diffraction when illuminated by white light from the sun or a tungsten filament lamp from the direction of the original reference beam. In effect, this hologram provides its own color filter because only one frequency in the visible region is coherently reflected, while all others are incoherently scattered, absorbed, or transmitted. Because of the large number of planes, the "Q" of the resonant system is quite high, having a reflected bandwidth of approximately 100 Å. The resonant frequency

(16) K. S. Pennington, *Microwave*, Oct., 1965.

(17) F. G. Kaspar and R. L. Lamberts, paper presented at San Francisco Meeting of American Optical Society, 1966.

(17a) G. W. Stroke and A. Labeyrie, *op. cit.*

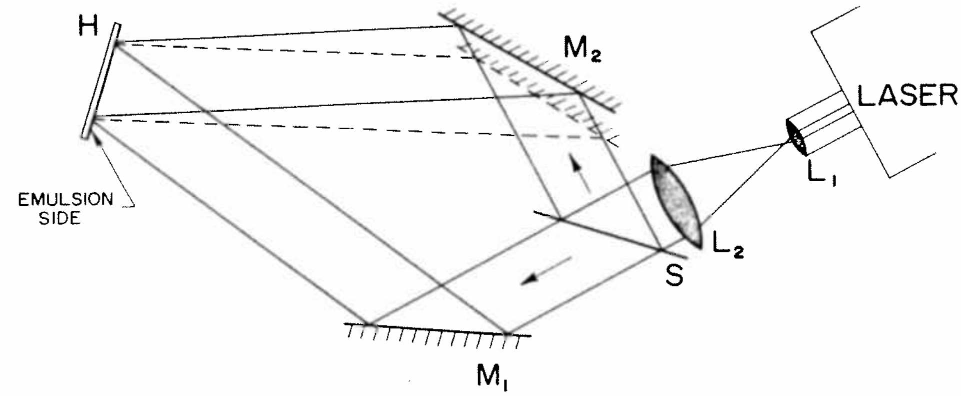

Fig. 37–17

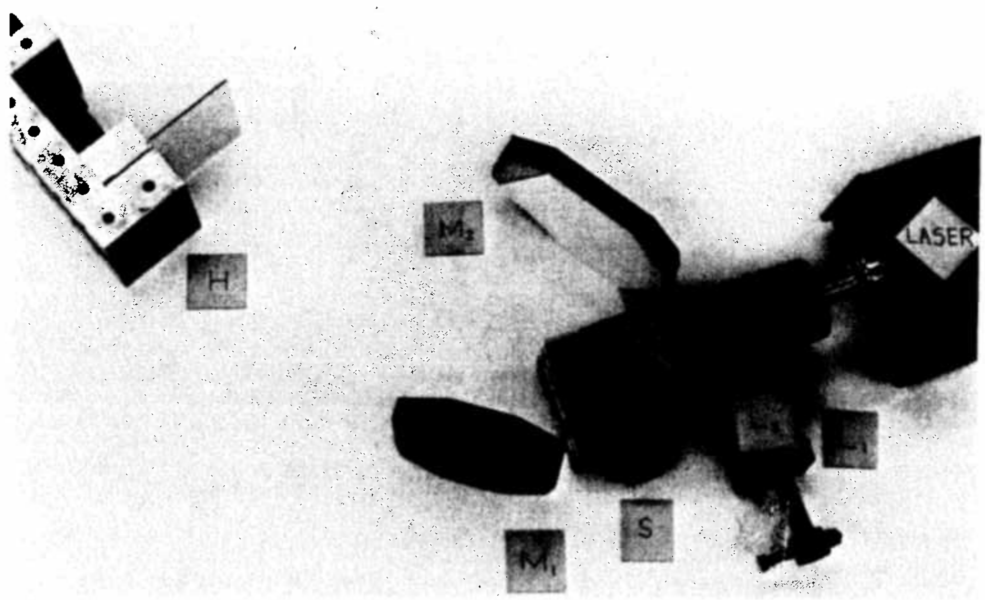

Fig. 37–18

can by varied slightly by moving the white light source, thus changing the angle of incidence, or by changing the temperature of the hologram. Usually, the emulsion shrinks slightly during the processing, and the color of the reconstruction is shifted to that of a higher frequency. This is fortunate, in a way, because the human eye is more sensitive to green than to red, assuming a He–Ne laser is used. If the shrinkage must be remedied, the finished hologram can be soaked in a solution of triethanolamine.[18]

If the light used in the construction of a hologram comes from more than one type of laser, say a He–Ne and an argon laser, multicolor holograms can be made.[18a] Here each frequency causes one set of three-dimensional diffraction patterns to be formed, and the finished hologram becomes a multiple resonant system.

37–5 Practical Hints for Constructing and Demonstrating Holograms

Few projects are as exciting to students as the construction of a good hologram. Depending on the quality and complexity desired, the equipment

(18) Private communication with G. W. Stroke.

(18a) L. H. Lin *et al.*, *op. cit.;* A. A. Friesam and R. J. Fedorowicz, *op. cit.*

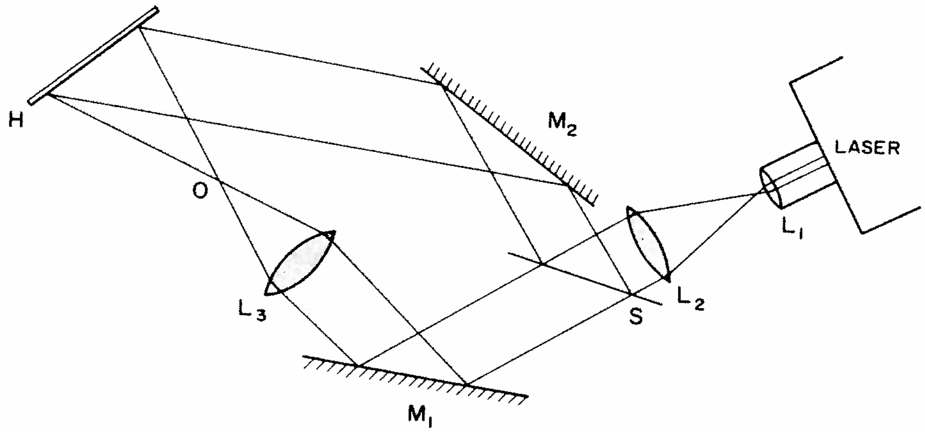

Fig. 37–19

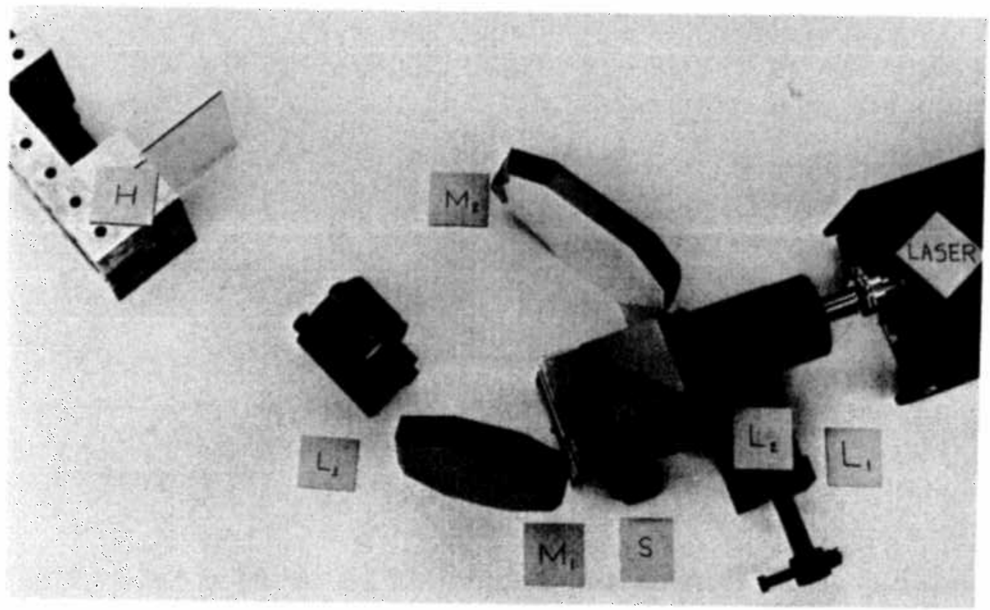

Fig. 37–20

requirements[19] vary from standard laboratory odds and ends to that costing tens of thousands of dollars. But always, a laser is a practical necessity.

We have made good holograms of varying complexity using a commercial 2 mW He–Ne laser,[20] as well as ones home-built according to the suggestions of Vander Sluis, *et al.*[21] The power requirement is unimportant if a mechanically stable system is available in a thermally stable environment. Following are some important points to remember, in addition to what has already been discussed.

[19] A medium price integrated set of apparatus capable of making high quality holograms of various kinds is sold by the Gaertner Scientific Corp., Chicago, Illinois.

[20] Model LAS-101 made by Electro Optical Assoc., Palo Alto, California.

[21] K. L. Vander Sluis, *et al.*, *Am. J. Phys.*, **33**, 225 (1965).

37–5.1 Stability Requirement

This depends *entirely* on the angle between the reference and the object beams. In general, the smaller the angle, the lower the spatial frequency and the less stringent the stability requirement. Actually, holograms can be made with the film hand-held.[22,23] For angles exceeding 10 deg, support

[22] G. W. Stroke, D. Brumm, and A. Funkhouser, *J. Opt. Soc. Am.*, **55**, 1327 (1965).

[23] G. W. Stroke *et al.*, *J. Opt. Soc. Am.*, **57**, 110 (1967).

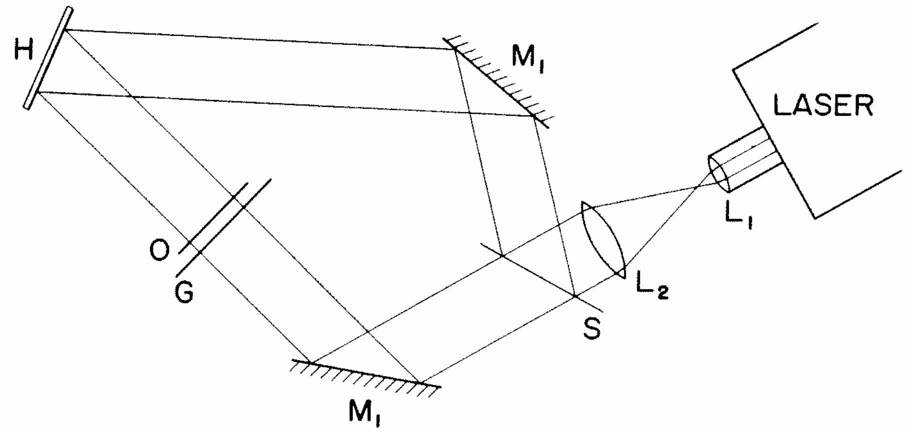

Fig. 37–21

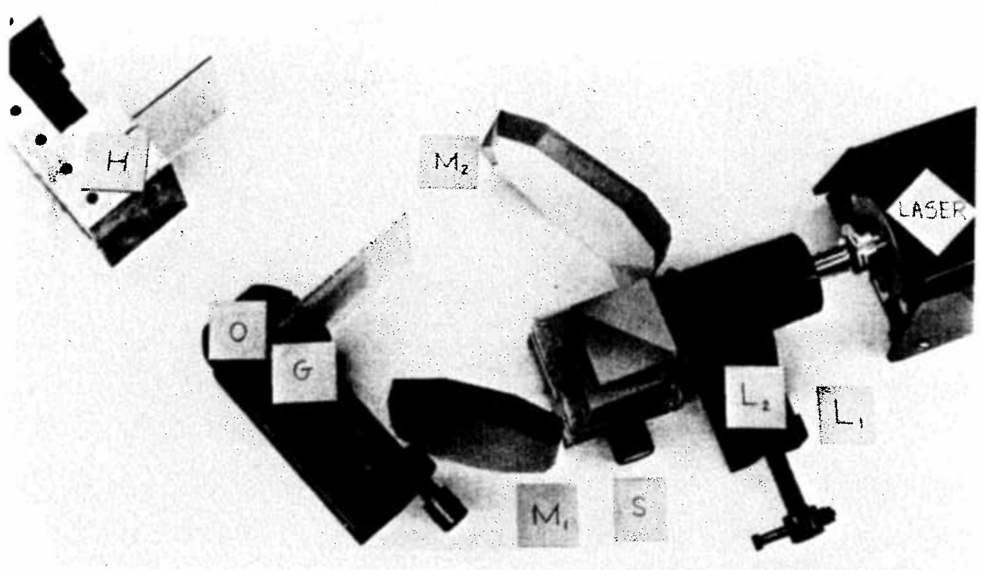

Fig. 37–22

the system on a heavy solid surface resting on a vibration-absorbing medium such as an inflated inner tube. If the photoplate has been handled, it should be allowed to reestablish thermal equilibrium with its environment before making the exposure. If a pulsed laser is used, the stability requirement becomes almost nonexistent. But other problems will come up.

37–5.2 Coherence Requirement

Ordinary lasers have coherent lengths not exceeding a few tens of centimeters. In general, the higher the operating TEM mode, the shorter the coherent length. For this reason, carefully arrange the geometry so that the optical paths for the reference and the object beams are approximately equal, each being measured from the beam splitter. If the paths must be different, they should differ by integral multiples of $2L$, L being the length of the laser cavity.

37–5.3 Emulsion Resolution

The spatial frequency on the prospective hologram dictates the resolution required of the emulsion. In general, use Kodak 649–F film or plate, and process as recommended. (It has a resolution of several thousand lines per millimeter.) On the

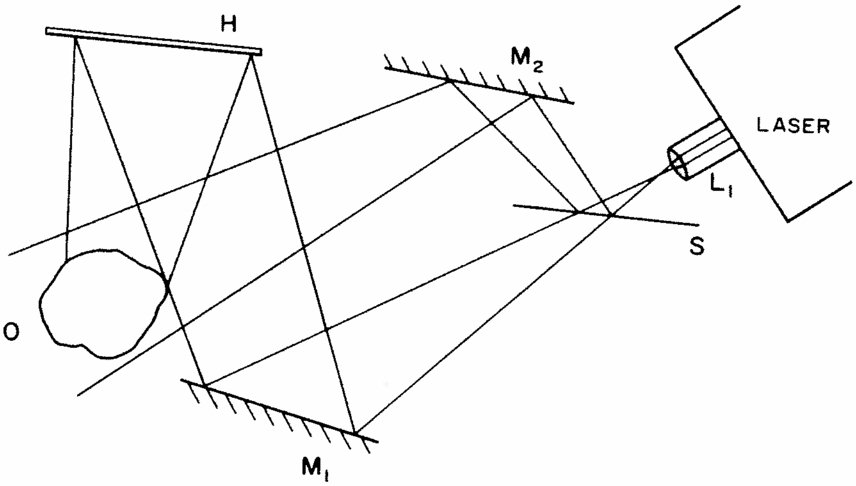

Fig. 37–23

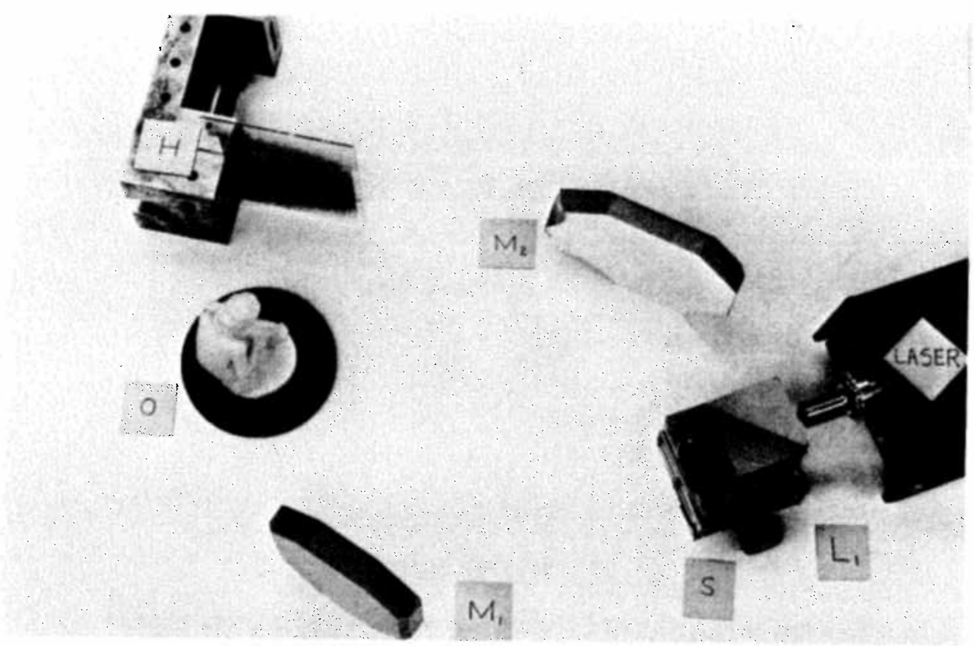

Fig. 37–24

other hand, if the spatial frequency is not to exceed 50 lines/mm, Polaroid P/N film can be used.[22]

37–5.4 Actual Optical Arrangements

Figures 37–17 (solid lines) and 37–18 show an actual setup for constructing a sine grating. In these and figures to follow, the symbols and their meanings are:

L_1–20× microscope objective

L_2 and L_3–large aperture, short focal length lenses

M_1, M_2, and M_3–first surface totally reflecting mirrors

S–beam splitter

O–object

H–emulsion for making grating or hologram

G–ground or opal glass

Note that the paths SM_1H and SM_2H are approximately equal. With a one-milliwatt (1-mW) laser and beam diameters of about 3 cm, the exposure time on Kodak 649–F emulsion is approximately 1 sec. Because of the thickness of this emulsion,

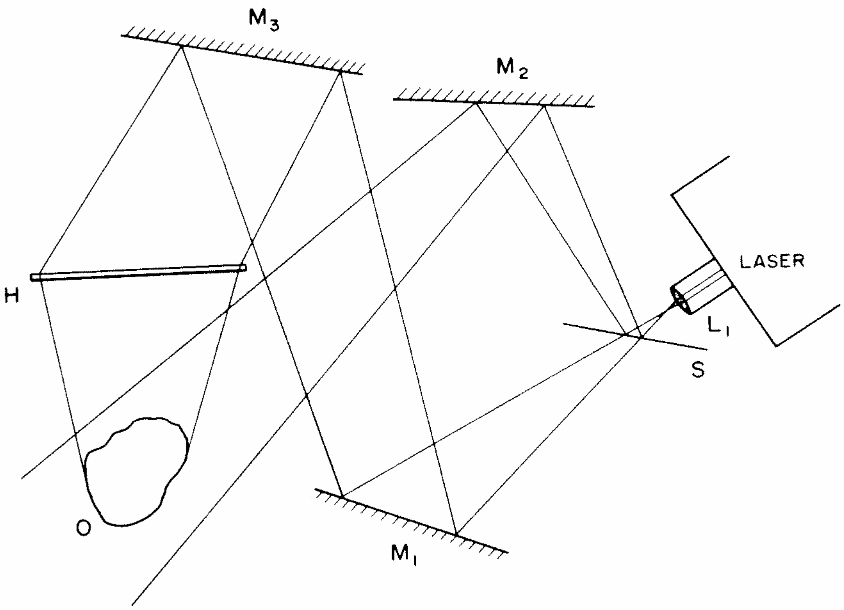

Fig. 37–25

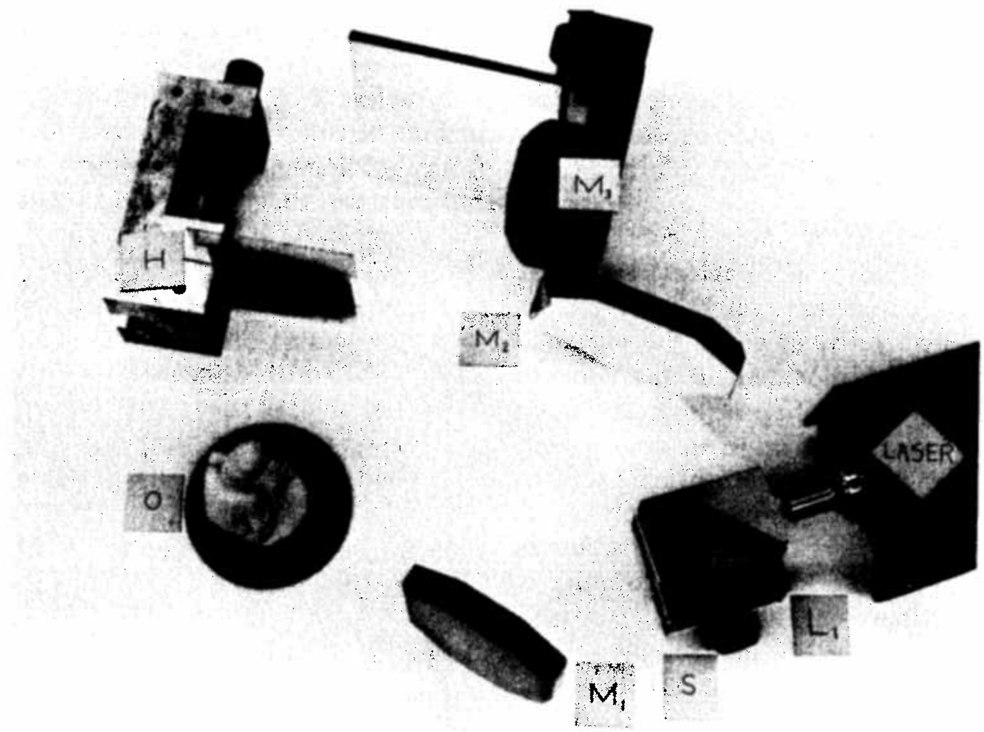

Fig. 37–26

the resultant grating will show sideband suppression (Sec. 37–4.6). A lower resolution emulsion can be used if θ is decreased. The exposure time, as well as the intensity ratio, has to be experimentally determined.

To make a beat grating, the same setup is used. After the initial exposure, M_2 is moved 2 or 3 cm, as shown by the dotted lines on Fig. 37–17, and exposed again after the mechanical vibration caused by the adjustment has subsided. The increase in the total exposure time will not significantly affect the quality of the grating.

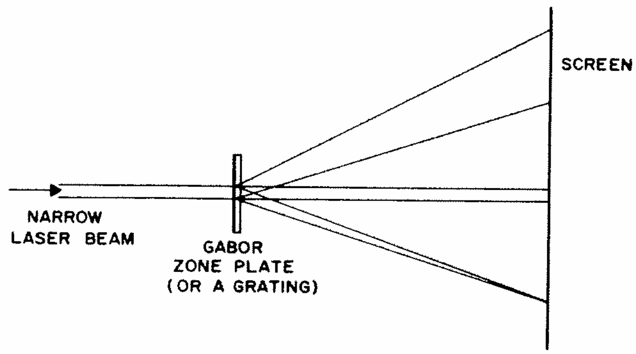

Fig. 37–27

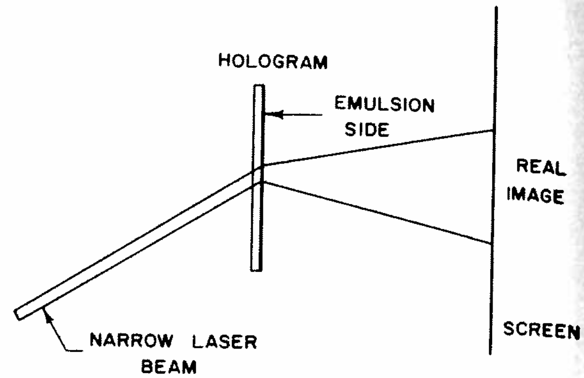

Fig. 37–28

The Gabor zone plate demands a minor change from Fig. 37–17, as shown in Figs. 37–19 and 37–20. A lens L_3 is placed between M_1 and H and causes an apparent point object O to be formed. The focal length of the resultant Gabor zone plate will be the distance between O and H. If a longer focal length is desired (which will be more suitable for demonstration to a large audience), a negative lens can be used instead, thus forming an apparent object point at a distance longer than the dimension of the whole arrangement. The intensity ratio should be adjusted by either using neutral density absorbers or by additional beam splitters (Sec. 37–4.7).

Figures 37–21 and 37–22 show a configuration for making a hologram of a complex transparent object—a 35-mm transparency. A piece of ground glass G is placed directly ahead of the object to provide diffused illumination. Again, the intensity ratio should be adjusted before exposure.

Figures 37–23 and 37–24 show an arrangement for making holograms of three-dimensional objects. Paths SM_2OH and SM_1H are approximately equal. As in all cases, the intensity ratio must be adjusted. Exposure time for Kodak 649–F is in the order of several minutes with a 1-mW laser.

Figures 37–25 and 37–26 show a method of making Lippmann-Bragg white light reflection holograms (Sec. 37–4.7).

37–5.5 Demonstrating

The gratings can be demonstrated to a large audience (of several hundred) using a laser having an output of 2 mW or more. The simple arrangement is shown in Fig. 37–27. The natural laser beam impinges directly on the gratings, and the diffraction pattern is shown on a screen. The separation between the grating and the screen should be equal to the focal length of the Gabor zone plate.

If a laser is not available, the demonstrator can pass the grating around the audience and have them look through it at a spectral discharge (a sodium lamp, for example).

There is no efficient method of showing a hologram of a three dimensional scene to a large audience unless a 50–100-mW laser is available. The natural narrow beam is directed on the hologram from the direction of the original reference beam, *but with the hologram turned backwards,* as shown

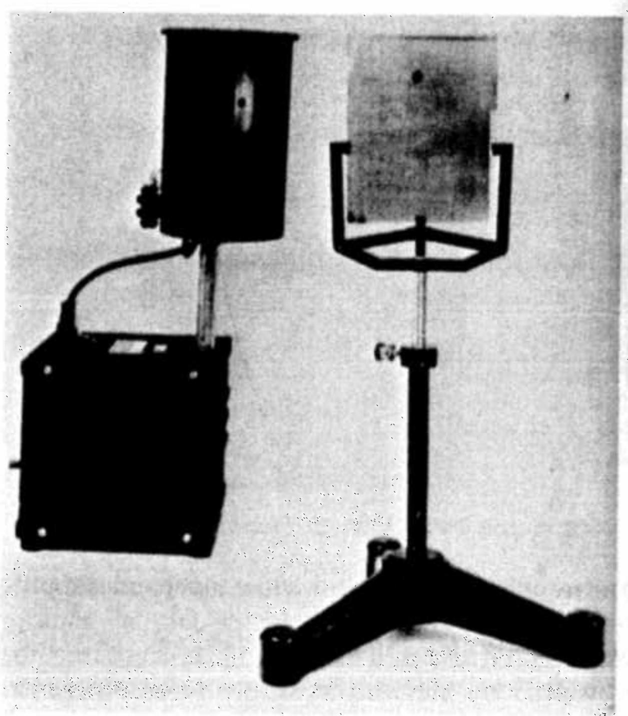

Fig. 37–29

in Fig. 37–28. A small screen (a white card) is positioned as shown where the real images are to be projected. In general, the depth of field is improved by making the illuminating beam narrow, with a corresponding sacrifice in resolution. By moving the beam about the hologram, changes in perspective can be observed. The reason for this procedure was explained in Sec. 37–4.6.

It should be noted that a laser is not necessary for viewing any hologram. The simple reason is that in the reconstruction the diffraction takes place locally and only a very short coherent length is required. This certainly is not the case during construction. A convenient corridor demonstration can be set up as shown in Fig. 37–29. A mercury discharge is used, and a small aperture is placed near the tube to approximate a point source. The entire system should be situated in a darkened area, or it should be placed in a dark cabinet. Without filters, each line in the mercury discharge will produce a separate set of image sizes directly proportional to the wavelength.