

1 HOLOGRAPHY

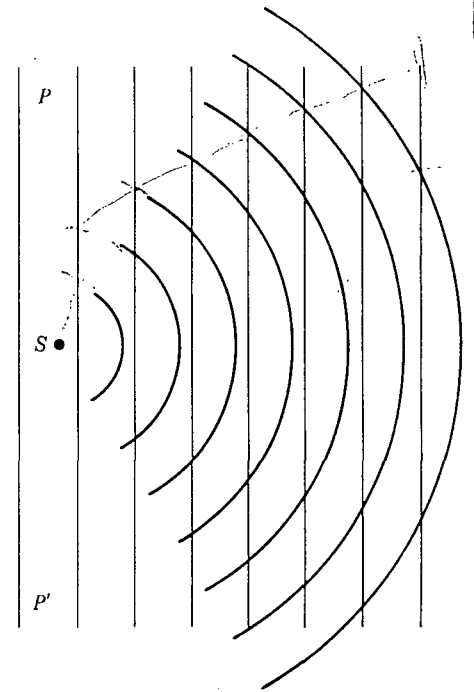


FIGURE 31A
The interference of coherent waves scattered from a point source, with plane waves, will give rise to a hologram in the form of a Gabor zone plate.

31.1 THE BASIC PRINCIPLES OF HOLOGRAPHY

In the preliminary stages Gabor's technique was to cause a beam of coherent light to be scattered from an object and then allowed to overlap an unobstructed coherent beam. The two sets of waves coming together on a photographic plate, placed in front of the object, would produce interference fringes.

Consider the interference pattern caused by coherent monochromatic plane waves incident from the left onto a point scatterer (see Fig. 31A). At the plane of the photographic plate HH' to the right, bright and dark concentric circles will be formed due to constructive and destructive interference between the *scattered light* and the *direct reference beam*. Upon development, the plate is found to contain light and dark partially absorbing fringes, as predicted.

This pattern, called a *Gabor zone plate*, is similar to a *Fresnel zone plate* treated in Chap. 18, except that the light and dark fringes shade continuously into each other (see Fig. 18I). The ring pattern is a great deal like the circular fringe pattern produced by the Michelson interferometer [see Fig. 13P(a) and (b)].

Since the reference beam is assumed to be in constant phase across the surface of the hologram plane, the interference fringes at any point P will be separated by an amount Δr , corresponding to a difference of path length of one wavelength of light as measured from S^* (see Fig. 31B):

$$\lambda = \Delta r \sin \theta \quad (3)$$

The term *holography* comes from the Greek meaning *whole writing*. It is a two-step process by which (1) an object illuminated by coherent light is made to produce interference fringes in a photosensitive medium, such as a photographic emulsion, and (2) the illumination of the developed interference pattern by light of the same wavelength produces a three-dimensional image of the original object. The viewed images produced by this process have the appearance of the original object, including the differences in perspective one obtains with a change of the viewer's observing position—a full three-dimensional image.

The principles of holography were first put forward by Dennis Gabor, of the Imperial College of Science and Technology, University of London. Gabor's invention consisted of a method for improving the resolution of images obtained with an electron microscope, and his announcement of the concepts was published in 1948.* Recognition was made of his work at that time, and it was not until the development of the laser in 1960 that his basic ideas became more than a laboratory curiosity. He was awarded the Nobel prize in physics in 1971 for his *three-dimensional lensless method of holography (holography)*.

* For finding the radius of the rings we use the geometry of Fig. 31B. The

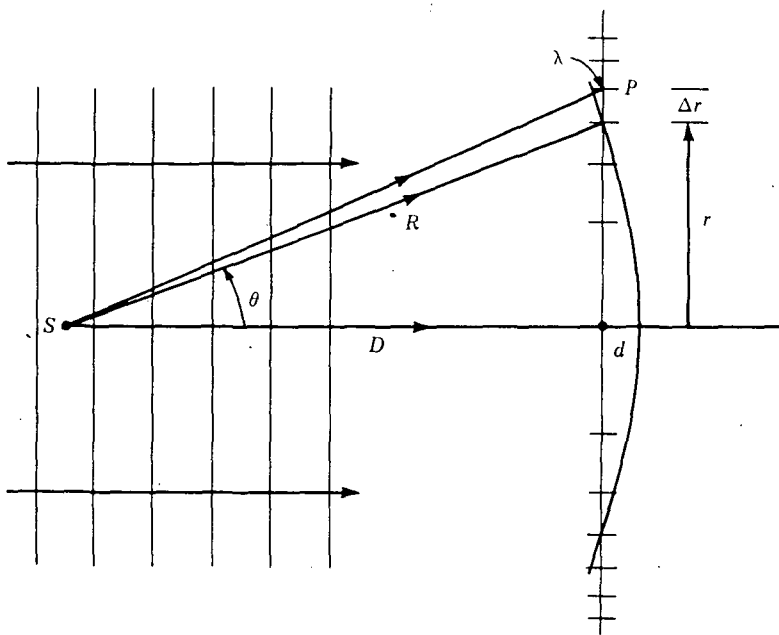


FIGURE 31B
The geometry for the fringe spacing Δr in a Gabor zone plate. P marks points of constructive interference which develop as black fringes on a hologram.

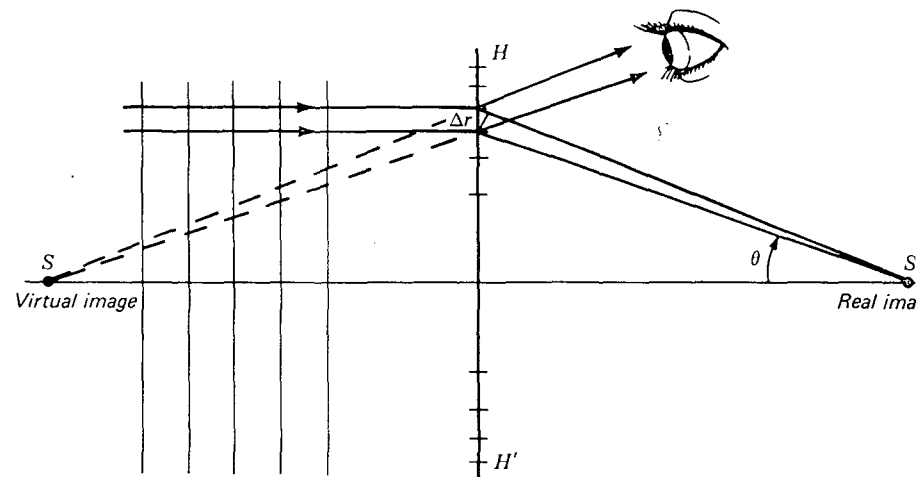


FIGURE 31C
Point images, both real and virtual, formed by plane coherent light falling on Gabor zone-plate hologram. The virtual image can be seen at S by the eye, and the real image can be formed on a screen at S' .

This plate is then illuminated by plane coherent waves, as it was in the making, in the absence of the scatterer. The light formed by interference between the light from the dark bands will now produce a first-order interference maximum at the angle given by Eq. (31a) [see Fig. (31C)]. This light will therefore appear to diverge from S . Since all points from the hologram will produce diffracted light propagated as if from S , a virtual image is created and can be viewed from the right of the hologram.

Suppose now that two scattering centers were originally present on the left. These now will create a Gabor zone plate. Moreover, the modulation intensity of each zone plate will be proportional to the scattered light intensity provided the photographic response is linear. The reconstruction will therefore produce a virtual image with two scattering centers, each with its proportionate intensity.

The argument can now be extended to a distributed scattering source corresponding to a continuum of scattering centers. The hologram will now consist of a continuum of superposed zone plates (see Fig. 31D). Upon reconstruction, the diffracted virtual image should appear exactly like the original object as viewed from the right of the hologram.

Although the basic principles of Gabor's *on-axis hologram* are straightforward enough, the application of these principles suffered from several technical difficulties,

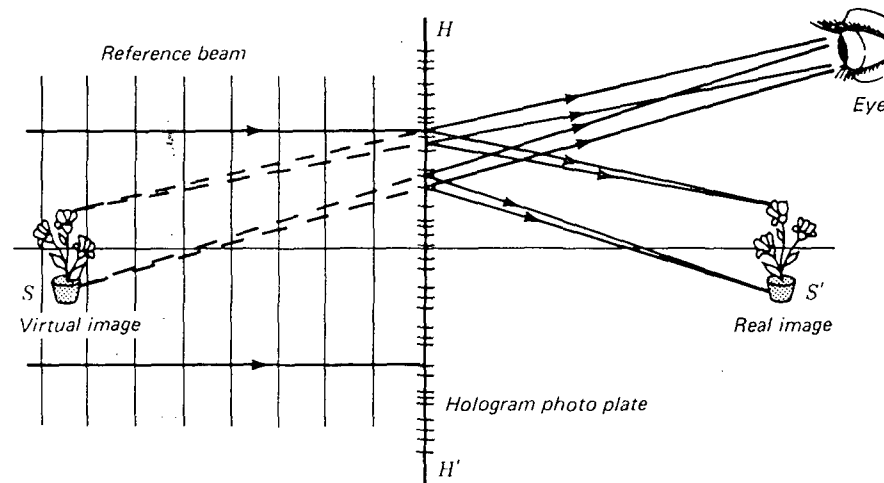


FIGURE 31D
An object at S and a reference beam form a complicated array of Gabor zone plates on HH' , which upon development is illuminated by the same reference beam. The eye now observes a virtual image at S and a real image at S' . A screen or photographic plate at S' will now register this real image.

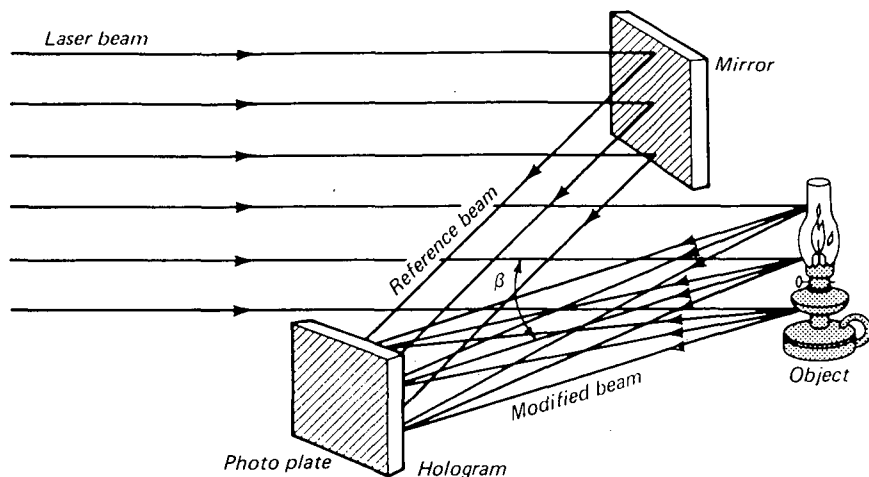


FIGURE 31E

Monochromatic, coherent laser light is reflected, unchanged, onto a photographic plate. Part of the beam is modulated by its reflection from an object to the same plate. When developed, the plate reveals interference fringes called a hologram.

most significant being the lack of a sufficiently coherent light source. With the advent of the laser, the outlook for holography changed dramatically.

However, a second difficulty appeared in the form of a real image caused by light diffracted in the opposite direction. This image was generally observed in front of the first image, and therefore it was in the way when viewing the virtual image (Fig. 31D).

The next major breakthrough was made in 1962 by Leith and Upatnieks, who developed the idea of the off-axis hologram.* This can be seen as a simple extension of the Gabor hologram, using an off-axis section of the holographic plate. This variation was made possible by the increased coherence length of the laser beam.

This simple variation not only separated the real from the virtual image line of sight but allowed for separate handling of the reference and scattered beam. The object could now be illuminated from any side or several sides. Moreover, it is not necessary that the reference beam be normally incident plane waves, provided that it is produced by the equivalent of a point source and that the reconstructing beam faithfully reproduces it.

One method of producing such a hologram is shown in Fig. 31E, where an incident laser beam is split into two beams, one of which changes direction as it strikes a plane mirror and the other is scattered by the object. At the photographic plate, the two beams interfere in a very irregular pattern, as shown in Fig. 31D. The angle between the scattered light and the reference beam will determine the density of the



FIGURE 31F

An enlarged section of a plane hologram made with $\lambda = 6328 \text{ \AA}$ from a He-Ne gas laser. (Conductron Corporation.)

fringes, or spatial frequency. If the angle is small, the spatial frequency will be low (fringes far apart), but visual interference of the real image will be severe. More often a mottled background can be seen, called intermodulation noise, due to fringes produced by the interference of light from various parts of the object.

By using larger angles, these effects can be eliminated, but the resulting spatial density will require high-resolution film, and particular care must be taken

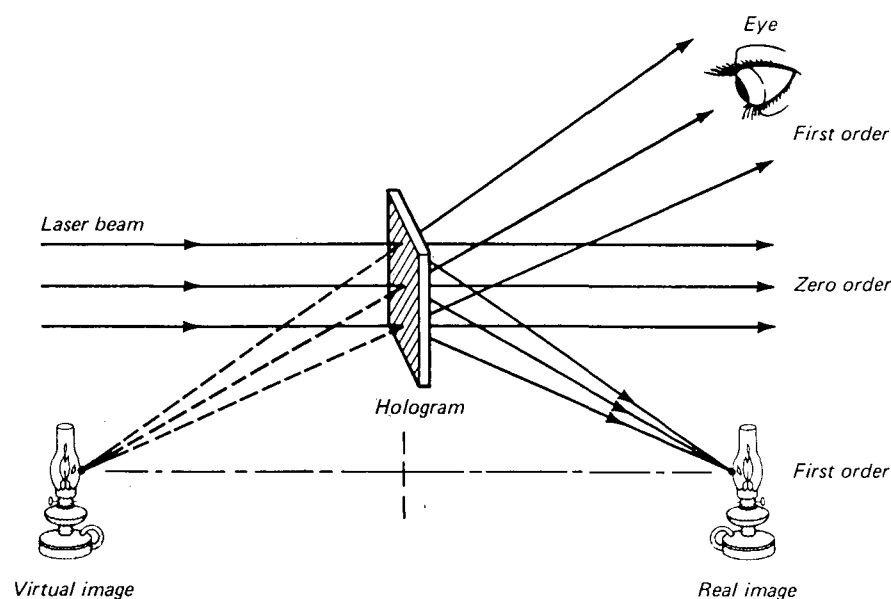


FIGURE 31G

The monochromatic, coherent laser beam is incident on a hologram, where it is modulated to produce two diffracted waves, the first order on each side. The remainder of the direct beam forms the unchanged zero order.

1.2 VIEWING A HOLOGRAM

To see the reconstructed object when a hologram is made, the photographic plate containing the interference fringes is placed in the monochromatic beam from the same laser used making the picture and with the same alignment. The diffracted waves diverge as if they came from the virtual image. The lens of the eye focuses these waves on the retina, where a real image is formed (see Fig. 31G).

The original waves producing the interference fringes and the waves reconstructing the image will be identical in all optical respects. The image is not only three-dimensional but in perspective as well, and will change as the viewer moves his head. As the observer moves his eyes to different positions, the rays of light entering each pupil come through small but different sections of the fringe pattern on the hologram, and he sees the object in different perspective. If he finds an object hidden behind another, he can move his head and look around the nearby obstacle, thereby seeing the hidden object.

If the reconstruction beam does not reproduce the original reference beam symmetrically, the image will be distorted. Illumination by light of wavelength different from the original will cause both a change in size and displacement of the image. Illumination by a spectral distribution will produce color fringing. The normal shrinkage of a photographic emulsion during development is sufficient to cause minor

If the hologram is broken into many small pieces, each piece will be a hologram of the complete object scene. However, the perspective will be limited according to the size of the piece and there may be a loss in resolution.

A hologram made in the above fashion might be thought of as a negative. Every hologram, however, is a positive print. If any hologram is copied by contact printing, thereby reversing black for white and white for black, it will produce the same images and not a reversal. This is similar to a Fresnel zone plate, where complementary zones produce identical bright spots as foci. For complementary zone plates see Fig. 181.

If the emulsion of a hologram is bleached by normal photographic processing after it has been fixed, the darkened silver grains are replaced by transparent grains of a different refractive index. Under these conditions the film will appear uniformly transparent. This changes an *absorption* hologram into a *phase* hologram, increasing its clarity.

The *real image* from a hologram can be formed on a screen, and a photographic plate located there can be developed into a real picture. This same image can also be observed by locating the eye beyond the real image, where it can intercept the rays diverging from their points of intersection in the three-dimensional image. The eye must be located far enough back, at least to the distance of most distinct vision of the object to be seen sharply.

The undistorted real image has some visual characteristics foreign to the natural senses. As shown in Fig. 31G, the image of the lamp is illuminated on the front face, and the real image displays that side even though it is spatially behind the surface and should obscure it. A hologram made using an opaque object produces a *pseudoscopic image* which displays contradictory visual cues, which must be seen to be appreciated. As a result, the real image is of limited use.

31.3 THE THICK, OR VOLUME, HOLOGRAM

The holograms discussed above have been assumed to have negligible thickness and are referred to as *plane holograms*. If the recording medium is thick with respect to the spatial frequency, the interference fringes act as a series of ribbons, somewhat like a venetian blind. The reconstructing beam will generally pass through many sets of such fringes. This third dimension has the effect of adding an additional constraint on the diffraction pattern produced in a way similar to Bragg scattering of X rays from crystals.

In the Bragg-scattering experiments, used so much in X-ray studies, the regularly spaced atoms in the crystal act like partially reflecting planes, scattering the incident beam in definite preferred directions (See Fig. 31H). In these preferred directions the waves reflected from adjacent planes differ from each other by exactly one wavelength and, being in phase with each other, produce constructive interference. The Bragg scattering relationship for these directions is given by

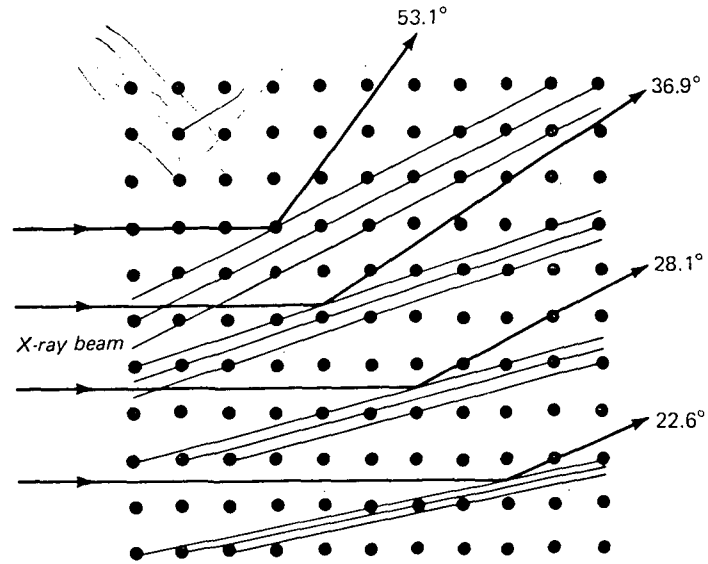


FIGURE 31H
Diagram of the reflection of X rays from the various atomic planes in a cubic crystal lattice.

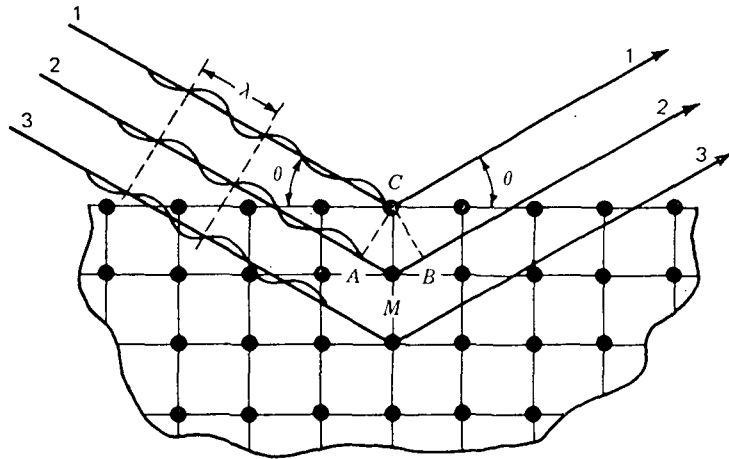


FIGURE 31I
Geometry illustrating the Bragg rule of reflection for X rays from the surface layers of a cubic crystal.

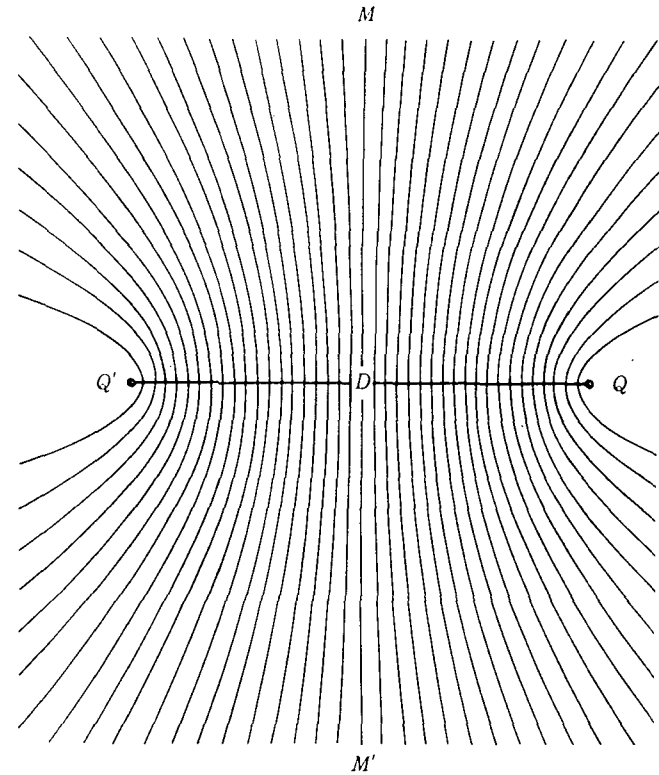


FIGURE 31J
Two point sources Q and Q' emitting monochromatic coherent waves constructively interfere along hyperboloidal surfaces.

where d is the distance between reflecting planes, λ is the wavelength of the wave and θ is the reflection angle shown in Fig. 31I. This principle of Bragg reflection forms the basis of a particularly simple geometrical model* that can be used to account for most of the features of the thick hologram.

First consider two coherent point sources of light waves Q and Q' , of wavelength λ , separated by a distance D as shown in Fig. 31J. Every point on the midplane M bisecting the line connecting the sources, will be equidistant from the sources and therefore be a point of constructive interference. Other surfaces of constructive interference can be found, each of which corresponds to a difference in path length from the two sources of an integral number of wavelengths. These surfaces can be shown to be hyperboloids, which are separated by $\lambda/2$ as measured along the connecting line between the sources.

* The simple geometrical model developed here for thick holograms is attributed to T. H. Jeong. The hyperboloids drawn in Figs. 31J, 31K, and 31L generated by computer. See T. H. Jeong, *Geometrical Model for Holograms*, *Jour. Phys.*, 43: 714 (1975).

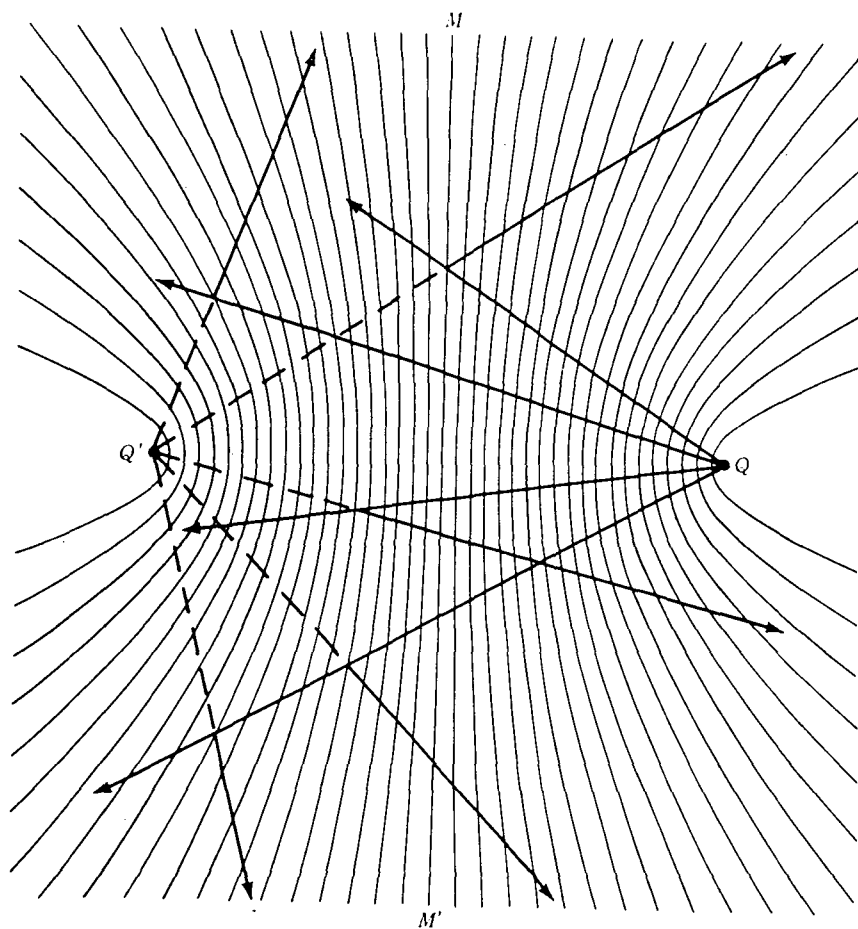


FIGURE 31K

Any ray from source Q can be reflected by any of the hyperboloidal mirrors and in such a direction that all rays appear to come from Q' .

Imagine now that each of these surfaces in the developed emulsion is a partially reflecting surface and that point Q acts as a source of coherent illumination. The midplane acts as a plane mirror, creating a virtual image at Q' (Fig. 31K); see Fig. 3E. Moreover, reflection from any portion of any of the hyperboloidal surfaces will obey the law of reflection and emerge as if they diverged from Q' . The reflected pattern from any volume occupied by the fringe surfaces will then produce a virtual image at Q' .

Consider now that Q in Fig. 31L is a primary source, e.g., a laser. Point Q' is a secondary coherent source, a scattering center exposed to the primary laser beam. A thick photographic emulsion HH' is now exposed to the interfering light at an

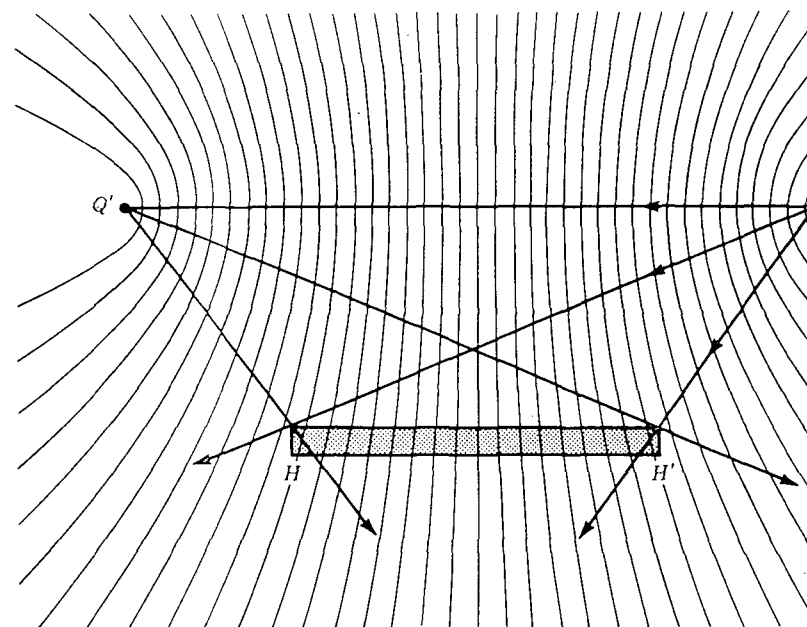


FIGURE 31L

A thick-hologram model which assumes that the interference between two monochromatic coherent point sources forms inside the recording medium a set of partially reflecting, absorbing, a hyperboloidal surfaces.

off-axis position. When the film is developed, it will contain darkened bands along the portions of the hyperbolic surfaces of constructive interference. The image consists of grains of silver. Actually, fringes may consist of a change of refractive index, as in a *bleached emulsion*, or simply a change of refractive index, as in a *bleached emulsion*, is sufficient. When this hologram is illuminated from point Q and viewed on the far side, a virtual image will appear at Q' (see Fig. 31M).

As with the plane hologram, the argument can now be extended to the formation of a hologram capable of producing the virtual image of an *object* (see Fig. 31N). Such a hologram would be thought of as a superposition of sets of hyperboloidal mirrors. When the hologram is viewed, each set of mirrors reflects light from the reference beam and forms an image of a point on the object.

31.4 MULTIPLEX HOLOGRAMS

One of the remarkable features of the thick hologram is its ability to produce multiple images from the same photographic emulsion. If the distance between the sources is smaller than the emulsion thickness, each ray of the reconstruction light from the direction of the reference beam will pass through several parti-

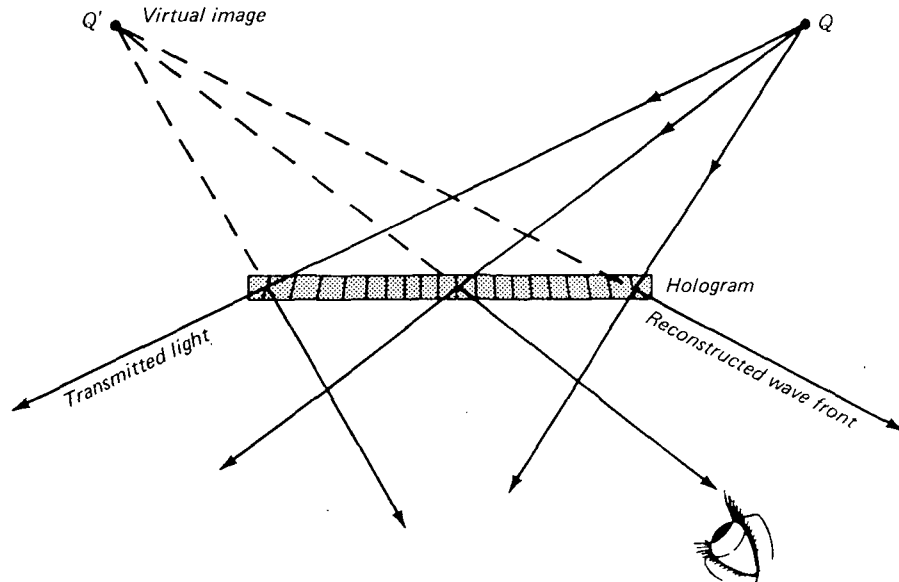


FIGURE 31M

The virtual image Q' is created by illumination of the thick hologram by a point source Q .

planes (see Fig. 31O). The reflected rays from each of these planes must be an integral number of wavelengths apart. If the reillumination beam forms an angle significantly different from the reference beam, the light reflected from the adjacent planes will no longer be in phase and the virtual image will no longer be visible.

It is therefore possible to produce many holograms in the same photosensitive medium, each with the reference beam at a different angle. When viewed later, each of these images can be separately viewed simply by varying the angle of the reference beam. This technique has been used to store hundreds of images in a single crystal of *lithium niobate*. The process is capable of storing an entire book in an appropriate medium by slightly changing the direction of the reference beam with each exposure. When viewing the finished hologram, one can "turn the page" by merely moving the reconstructing beam.

Alternatively, a multiplex hologram can be produced by appropriately moving the reference beam angle with time, thereby producing holographic motion pictures.

31.5 WHITE-LIGHT-REFLECTION HOLOGRAMS

One of the possible arrangements for producing white-light holograms is to place the photosensitive film between the reference beam and the object (see Fig. 31P). Such a hologram is produced simply by illuminating the object through the photosen-

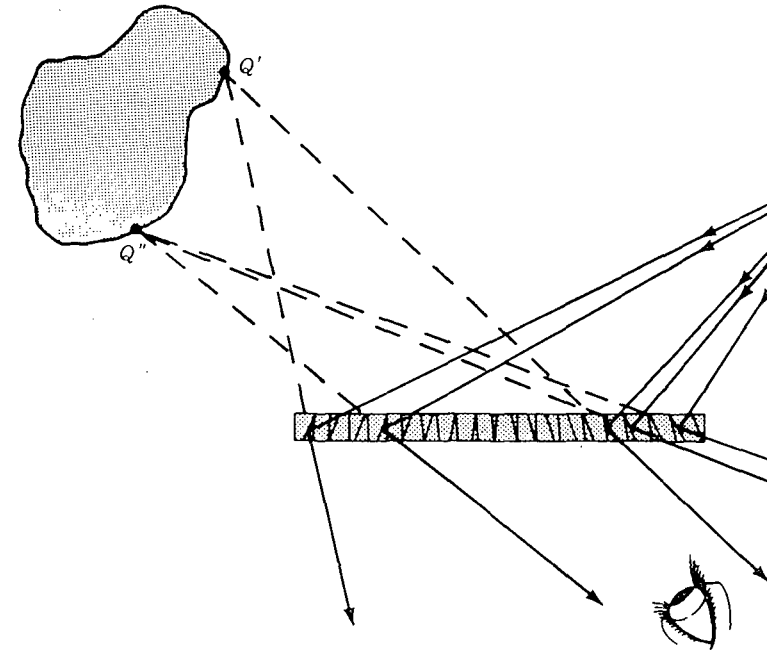


FIGURE 31N

A three-dimensional object is seen as the superposition from surfaces in the thick hologram by the interference of the reference light from points on the object.

sitive medium, thus avoiding beam splitters, mirrors, etc. In practice, intensity is so high relative to the scattered intensity that the technique shines on shiny objects located close to the recording medium. Better reflection can be made by separating the object and reference beams.

Since the reference and object beams are oppositely directed, the frequency is extremely high. A large number of reflecting planes are therefore separated by about a half wavelength of light. As a result, the reconstructed image must be of the same wavelength or the reflections from adjacent planes will be out of phase for constructive interference. Alternatively, if the hologram is viewed with white light (sunlight is an excellent source), the appropriate wavelength will be used to produce the reflected image. Ordinary photographic emulsions are not suitable as they tend to shrink during development.

The technique is especially useful in that a laser is not required. Moreover, if the hologram is produced by illumination by lasers with the *three additive primary colors* (red, green, and blue), the resulting hologram can be seen in full color when viewed in white light.

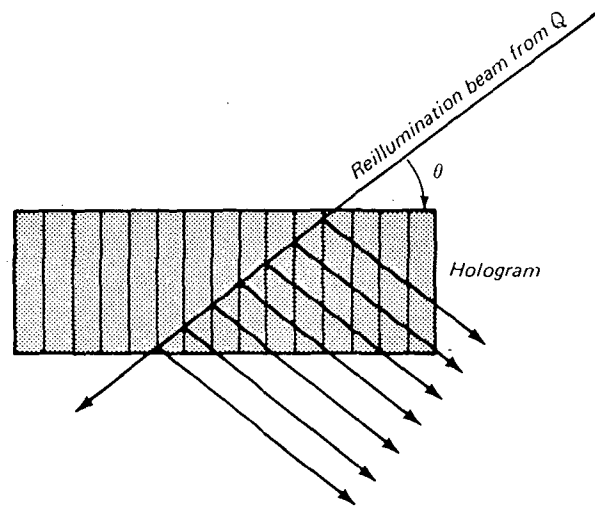


FIGURE 31O

Due to the Bragg reflection rule, all successively reflected waves will be in phase and reinforce each other only if the hologram is illuminated with the same wavelength of light and from the direction θ of the original reference beam Q .

31.6 OTHER HOLOGRAMS

A wide variety of holograms can be produced to achieve special effects. These include using lenses and mirrors and using other holographic images as objects.

One of the most impressive holographic images is formed by a 360° circular film. The technique was developed by T. H. Jeong using a photographic emulsion mounted on a cylindrical surface surrounding the object (see Fig. 31Q). The simplest, but not necessarily the best, method of illumination is to direct a diverging beam from above, illuminating the entire emulsion and object. Upon reillumination, the virtual image will be observed in the center of the cylinder, and can be viewed from all sides. If a high-intensity beam from a pulsed laser is used, there is no problem of using a jiggle-free table mounting.

At this point in the development of the art of photography, a brief comparison of lens photography and picture images with lensless photography and diffraction fringes should be mentioned. Both techniques have their advantages and disadvantages depending on the purposes for which they are used. The amount of information stored in an emulsion depends solely upon the smallness of the grain of the finished product. In the limit this appears to be determined by the size of the atoms and molecules of the storage medium itself. See Fig. 31R.

It would appear, for example, that the side-by-side storage of microscopic pictures can be equaled by the storage of superimposed sets of interference fringes in a thick hologram. On the other hand, the fine detail of the three-dimensional images

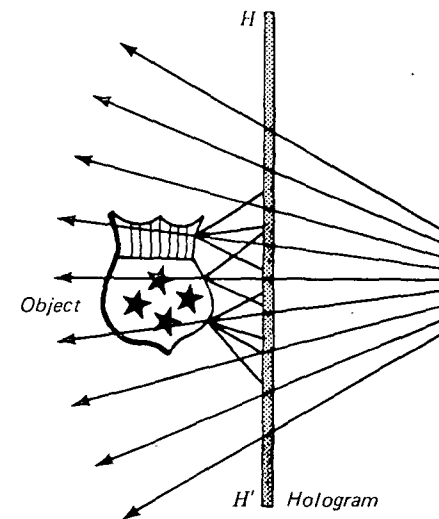


FIGURE 31P

Reflection hologram made from a single source and a transparent

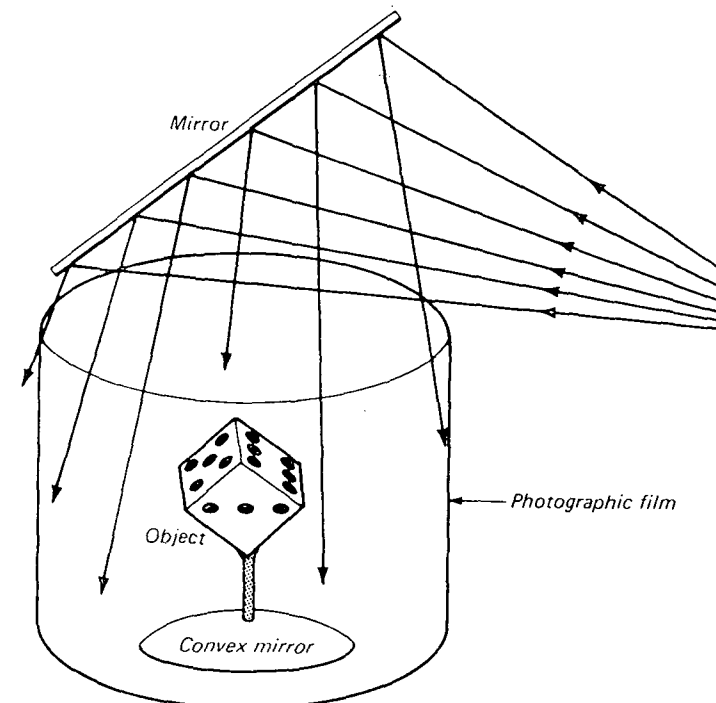
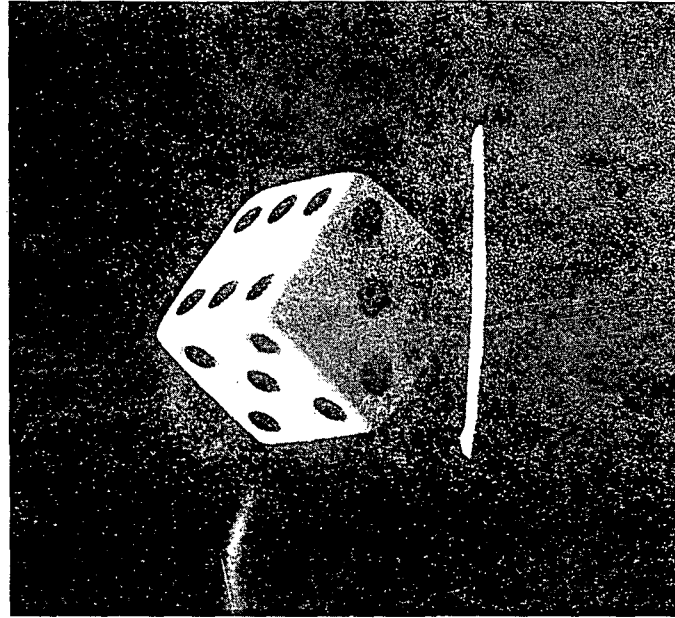
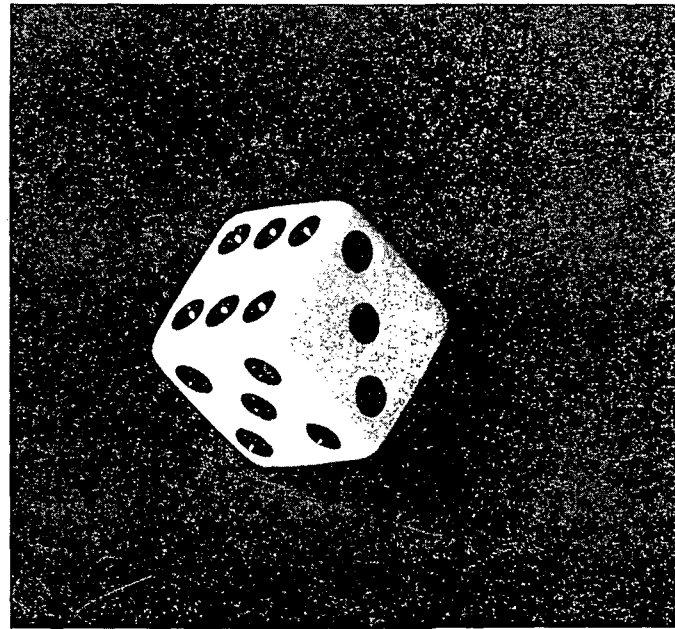


FIGURE 31Q

A 360° circular hologram can be made that can be viewed from



(b)



(a)

FIGURE 31R
 (a) A direct camera photograph of a 16-mm die made with an Exacta camera on 35-mm Plus X film. (Courtesy of A. D. White.) (b) Photograph of the same die seen in a 360° cylindrical hologram made with an arrangement like that shown in Fig. 31Q. (Metrologic Instruments Inc., Bellmawr, N.J.)

observed in full color and formed by a high-quality lens or concave compared with the three-dimensional images that can be stored in a used for later viewing.

31.7 STUDENT LABORATORY HOLOGRAPHY

Holography is such an intriguing subject that many students in the science wish to make and observe their own holograms. Briefly described here is a simple experimental arrangement that requires a minimum of space and equipment. Since the interference maxima in a hologram are about one-half wavelength, very fine grain emulsions should be used and considerable care must be taken to avoid jiggling the optical components during exposure.

To reduce the vibration hazard, all components, including the camera, should be mounted on a vibration-free block or heavy plate. For this purpose, a plate 70 to 90 cm square and 1 to 2 cm thick should be drilled and tapped in a regular pattern of holes for mounting the components rigidly. When all is in place for photography, this plate should be taken to a darkroom and placed in an automobile inner tube. A valve stem mounted on the outer edge of the tube is used for easy inflation and adjustment.

A relatively popular arrangement is to construct a sandbox, fill it with sand, and mount it on several inner tubes. Optical components are each mounted on the end of a solid wood or plastic rod, about 4 cm in diameter and 30 cm long, at the lower end. Pushed into the sand like a garden stake, this mount resists vibrations.

A diagram showing all components and their functions is given in Fig. 31S. M_1 , M_2 , and M_3 are front-silvered mirrors; MO is a microscope objective lens focusing the beam. A pinhole placed at the focal point of the microscope objective allows the undeviated laser beam to pass but will block out stray light from the laser or from diffraction by dust or the preceding optical components. The pinhole should be about $25\mu\text{m}$ for a $10\times$ objective and about $1\mu\text{m}$ for a $40\times$ objective.

Although a more uniform hologram is produced by such a setup, it is not essential and may not be worth the effort involved in aligning the pinhole, beam splitter, which is best if it reflects at least 75 percent of the light, and the plate should be 15 to 25° .

One major problem arises in the relative weakness of the modified reference beam from the object. Since the object scatters light in all directions, only a small fraction reaches the photographic plate. The maximum fringe contrast on the plate is theoretically attained when the total light from each beam is approximately equal (see Sec. 13.4). However, in practice, the scattered beam should be made weaker than the reference beam to reduce fogging of the plate due to incoherence noise.

Care should be taken to approximately equalize the two path lengths. Since the coherence length of the laser beam is reduced by multiple modes, the susceptibility to vibrations should be checked before using the method.

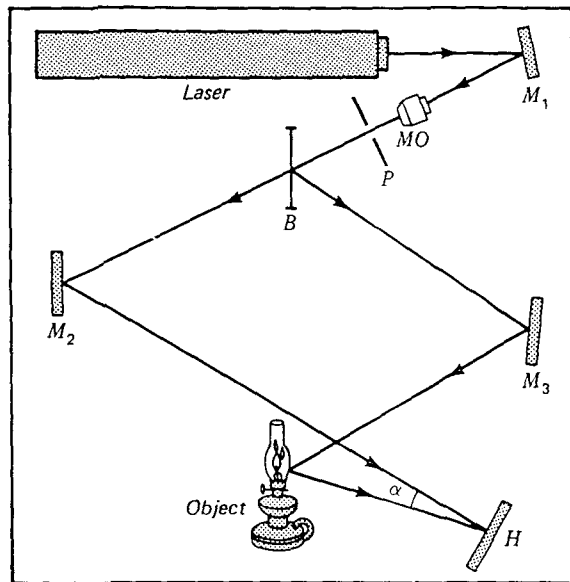


FIGURE 31S
Apparatus layout and components essential to making holograms. Components are rigidly mounted on a steel plate about 90 cm square, or on wooden stakes in the sand of a sandbox, resting on an inflated inner tube to reduce vibrations.

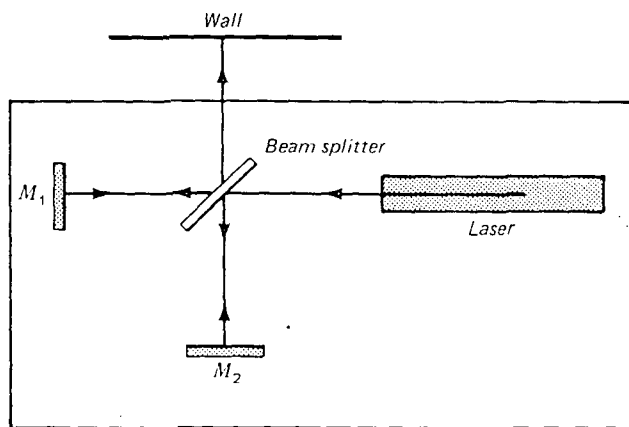


FIGURE 31T
Michelson interferometer arrangement for locating sources of vibration affecting the table set up for making holograms in the college physics laboratory.

arranging the various components to form a Michelson interferometer and projecting the fringes on a nearby wall (see Fig. 31T). A shift of one-half fringe during the time of exposure is enough to prevent any image of fringes at all, and a smaller shift is sufficient to reduce the image quality significantly. Such a test may indicate that components are creeping, that they are affected by air drafts, or that the system is jiggled by elevators, machinery, or people walking in the hall nearby. Appropriate countermeasures can then be taken. High-resolution film must be used, and several trial photographs are necessary before satisfactory holograms are obtained.

REFERENCES

- CAMATINI, E.: "Optical and Acoustical Holography," Plenum Press, New York, 1972.
 COLLIER, ROBERT J., CHRISTOPH B. BURCKHARDT, and LAWRENCE H. LIN: "Optical Holography," Academic Press, Inc., New York, 1971.
 FRANCON, M.: "Holographie," Springer-Verlag, Berlin, 1972.
 GOODMAN, J. W.: "Introduction to Fourier Optics," McGraw-Hill Book Company, New York, 1968.
 HILDEBRAND, B. P., and B. B. BRENDEN: "Applications of Holography," Plenum Press, New York, 1971.

PROBLEMS

- 31.1 Coherent plane waves and the waves scattered from a point source fall together on a photographic plate as shown in Fig. 31A. If the wavelength of the light is 6563 \AA and the perpendicular distance from the point source to the emulsion is 5.0 cm , find
 (a) the radius of the tenth bright fringe from the center of the developed pattern.
 (b) What is the distance between the tenth and eleventh bright fringes? Assume that the waves at the center of the pattern are in phase and on the developed film are black.
Ans. (a) 0.83016 mm , (b) 0.07433 mm
- 31.2 The beam from a ruby laser emitting red light of wavelength 6943 \AA is used with a beam splitter to produce two coherent beams. Both are reflected from plane mirrors and brought together on the same photographic plate. If the angle α between these two interfering beams is 10° and the plate normal bisects this angle, find the fringe separation of the interference fringes on the plate.
- 31.3 Two point sources of coherent light Q and Q' are located 25.0 cm apart, as shown in Fig. 31J(a). (a) Find the fringe spacing along the center line QQ' if the wavelength of the light is 5461 \AA . (b) How many fringes are there per millimeter?
- 31.4 In one part of a thick hologram a number of ribbonlike fringes are found parallel to each other and $3.750 \times 10^{-4} \text{ mm}$ apart. At what angle with respect to these ribbons will light be reflected in the first order if its wavelength is 6563 \AA ? *Ans.* 61.053°