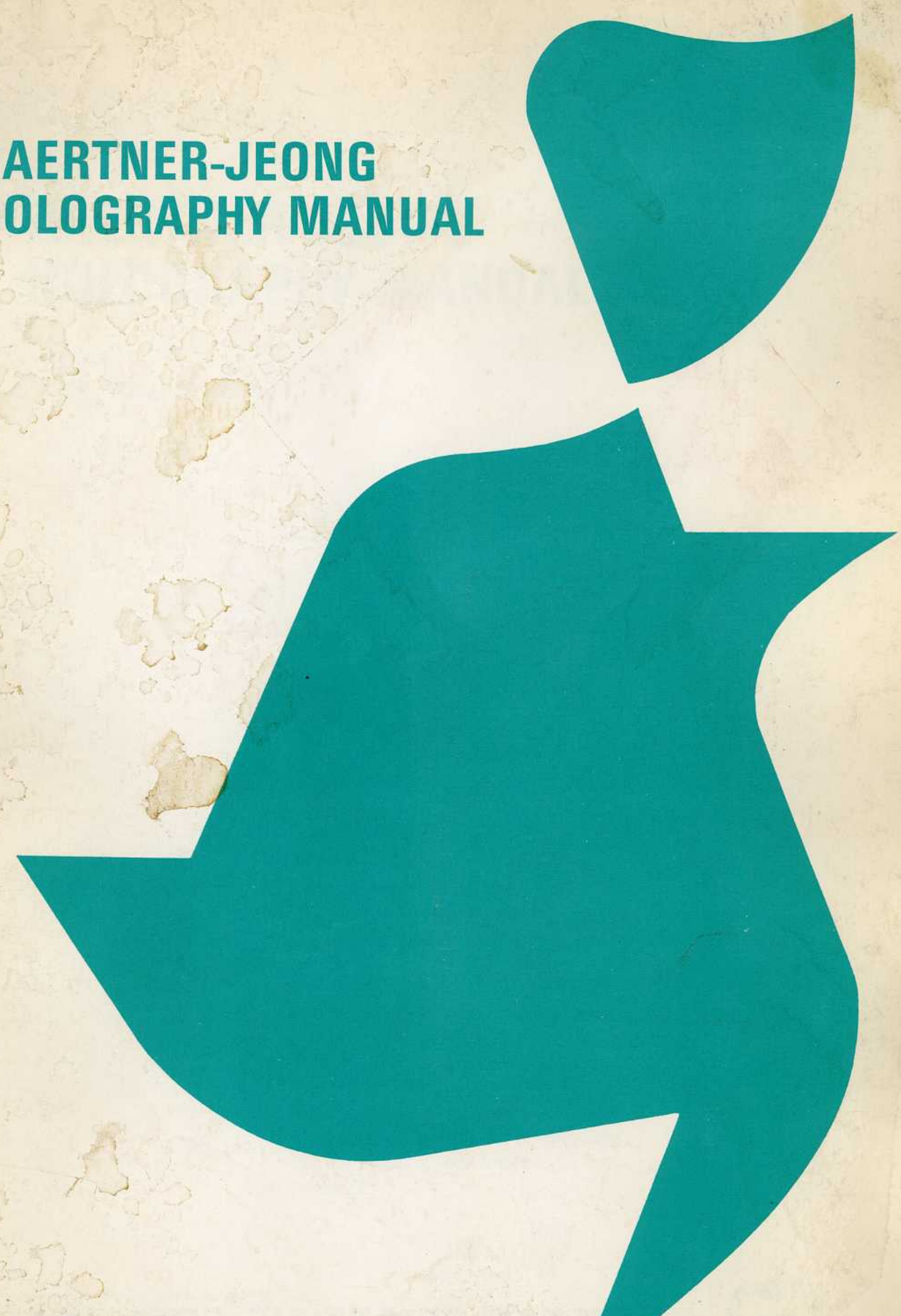
GAERTNER-JEONG
HOLOGRAPHY MANUAL



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GAERTNER-JEONG HOLOGRAPHY MANUAL

By

DR. TUNG H. JEONG

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ABOUT THE AUTHOR . . .

Dr. Tung H. Jeong is a rare blend of scholar, teacher and researcher. A Chinese American, Dr. Jeong came to the United States in 1948 to continue his education and to prepare himself for a career in teaching and research.

In 1956, Yale University honored Dr. Jeong for high academic achievement by conferring on him the title of Ranking Scholar. In 1957, he completed his undergraduate studies at Yale University and was granted a B.S. Degree in Physics. Following a summer at Battelle Memorial Institute, where he gained experience in Nuclear Reactor research, he moved to the University of Minnesota where opportunities for both teaching and research were provided. It was during this same period that he embarked on a graduate study program at Minnesota that eventually led him to a Ph.D. degree in Nuclear Physics in 1962. Post-doctoral research kept him at the University of Minnesota from 1962 to 1963. In July 1963, he joined the Physics Department faculty of Lake Forest College, Lake Forest, Illinois, where he is currently serving as an Associate Professor.

In the summer of 1966, Dr. Jeong accepted an invitation from Oak Ridge National Laboratories to work as a research participant in the Cyclotron Laboratory. Returning to Lake Forest College in the fall, he continued the challenging assignment of teaching an upper division course in physical optics and guiding students in independent research projects.

Dr. Jeong is a frequent contributor to leading scientific journals and magazines and is in constant demand as a speaker and lecturer before student, professional and scientific groups. He is an active member of several important scientific organizations, including the American Physical Society, Optical Society of America, American Association of University Professors, and the American Association of Physics Teachers.

It seems only fitting and proper, therefore, that a professional of Dr. Jeong's high caliber of performance be in a position to advise and assist in the research and development of new products for a leading manufacturer of scientific instruments, such as the Gaertner Scientific Corporation. Since the summer of 1967, Dr. Jeong has been on the technical consulting staff of Gaertner and has made numerous important contributions that have provided new product introductions, such as a new holography system for constructing and re-constructing of holograms.

GAERTNER SCIENTIFIC CORPORATION

Introduction

Recent advances in quantum electronics and communication theory have initiated a renaissance in the field of optical research. The subject of optics, previously taught only in departments of physics and astronomy in the universities, is now being added to the curricula of engineering departments. New industries and government projects in optics research are emerging at an unprecedented rate. Particular advances in coherent optics and information theory make optics an indispensable tool in both fundamental and applied investigations.

This is a manual on various optics experiments, classical as well as modern, elementary as well as advanced, using an integrated set of Gaertner components. Continued development will, from time to time, add new and useful accessories to this system, opening up additional possibilities and keeping up with recent advances.

Our basic philosophy of education is that students learn by doing, and that their initiative and imagination are better challenged by having them construct and calibrate the instruments using basic components.

Apparatus Description and Operating Instructions

The complete Gaertner-Jeong Holography System (see page 32 for catalog numbers) includes the new Gaertner Rectangular Optical/Instrument Bench with air suspension and peripheral metal frame; two mirrors; beam splitter; two beam spreaders; specimen table; film holder; spatial filter; beam deflector and laser. The mirrors, lenses, and beam splitter are mounted in yokes permitting tilt adjustment. All components except laser and beam deflector are mounted on rods in support tubes providing rotation and vertical positioning, and on controllable magnetic bases that can be mounted on the multi-rails, across the rails, or on the metal edges and sides of the frame in almost any orientation. The support for one of the beam spreaders incorporates a cross motion slide.

I. Rectangular Optical/Instrument Bench

The bench is composed of nine parallel steel strips 1½ inches wide and ¼ inch thick, mounted on a 2″ thick table made of a normalized high density material. It is mounted in a rigidly constructed metal frame and pneumatically supported to reduce shock and vibration to a minimum.

The metal frame is removable by lifting vertically. The eight locking screws in the sides, which serve to give rigid support to the entire unit during shipment, can now be loosened. The bench now rests only on the pneumatic supports and is vibration isolated. During an experiment, some components (such as mechanical shutters or motors) may introduce undesirable vibration to the rest of the system. They can be mounted on the isolated rim of the support container. If more or less air pressure is desired in the pneumatic supports, tilting the entire unit will expose the air inlets. Regular bicycle pumps can then be used.

II. Magnetic Bases

One of the most versatile features of this system is the magnetic base. Basically, it consists of a permanent magnet and a shunt. A lever is used to turn this shunt, "short circuiting" the magnet, so that it exerts no attraction to ferromagnetic material outside. When the shunt is turned the other way, the magnet is "on" and exerts a sufficient force to hold all of the accessories to the rails. The bottom of the base is ground to fit the rails on the rectangular optical/instrument bench. For increased versatility, it can be placed in a variety of positions on the bench, such as straddling two rails, or on the rim, and still exert a great attractive force. Also, the side opposing the lever is magnetically active, so that it can be attached to a vertical steel surface, with the carriage still upright. Each holography system includes nine of these bases, one of which has an accessory cross slide. The base takes any of the standard Gaertner components with a 13 mm rod. In addition, adapters are available for use with magnetic bases having 13 mm and 19 mm holes, permitting them to accommodate 10 mm rods.

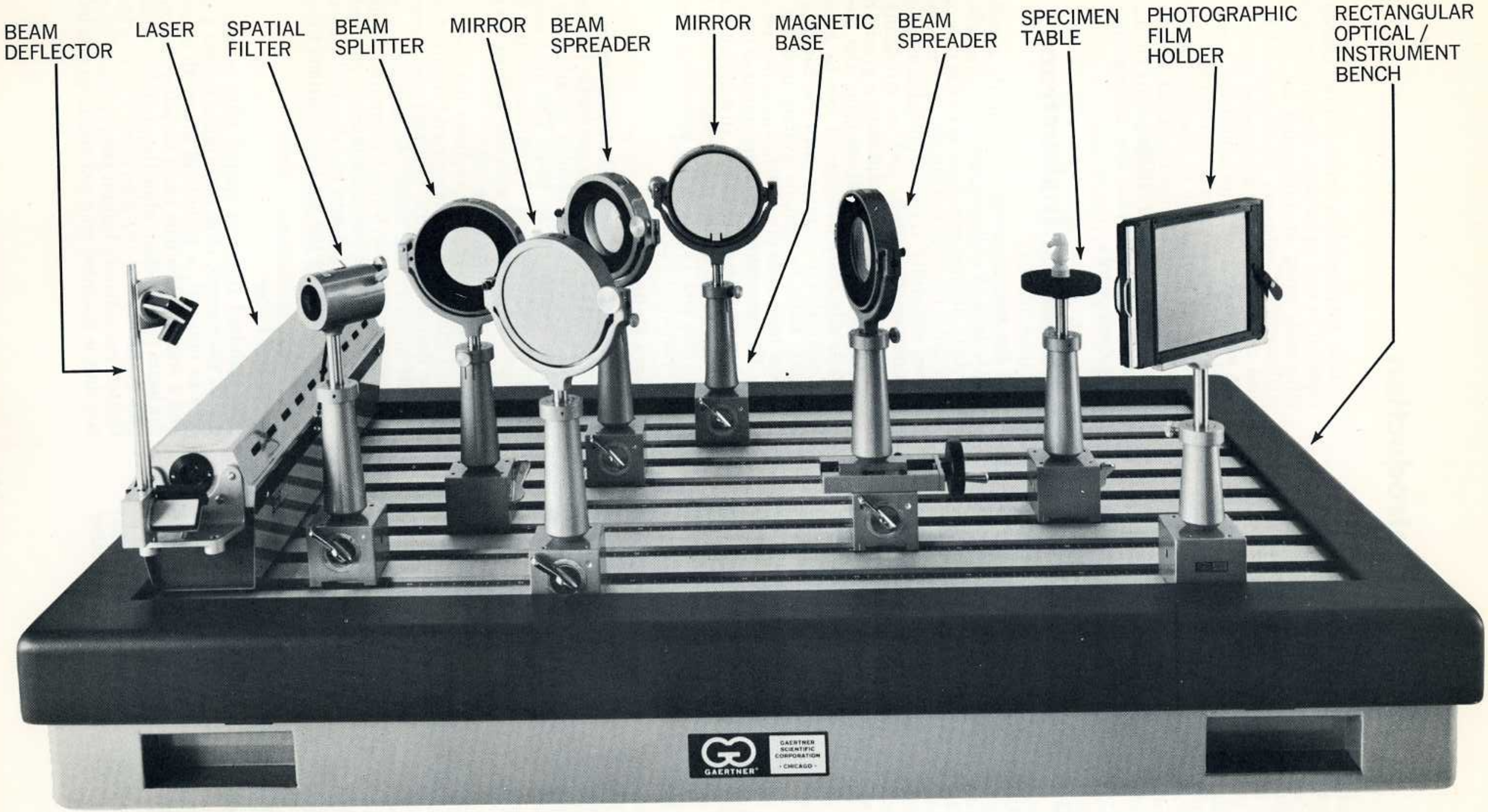
III. Beam Deflector

The Gaertner beam deflector consists of two first surface plane mirrors with magnetic holders, a vertical steel rod and a bracket for attaching the complete system to the laser. The dual magnet design permits rotating the mirrors around both vertical and horizontal axes, as well as vertical height adjustment on the rod.

The usual procedure is to direct the laser beam upward from the lower mirror and then deflect it in the desired horizontal direction and elevation by the upper mirror. Since the mirrors are held by magnets, they can be easily removed for other uses. The vertical rod with mirrors and holder can also be threaded into the standard Gaertner magnetic bases for use at other positions than on the laser.

IV. Spatial Filter

The standard Gaertner spatial filter consists of a 10X microscopic objective (other powers available as options), a pinhole of about 25 microns and a shutter. The lens has a focusing motion in the beam (z) direction while the pinhole is adjustable in the (x) and (y) directions. The shutter is located immediately behind the pinhole. The entire unit is mounted on a rod and magnetic base.



GAERTNER-JEONG HOLOGRAPHY SYSTEM

(See page 32 for Cat. No.'s)

The pinhole is supported on a magnetic disk, and can be easily pulled off from the centering disk during preliminary alignment.

The function of the unit is three fold:

1. The laser beam is focused to a small point by the lens and then spread out.

2. The pinhole permits the focused light to go through, but "filters out" light that is randomly scattered by dirt, dust, or imperfections in the lens. Internally reflected beams between lens elements are also blocked out.

3. The shutter is located in a very strategic position which can turn the beam completely on or off in a minimum time.

V. Mirrors, Lenses, and Beam Splitters

The standard holography system includes three first-surface mirrors 100 mm in diameter, two divergent lenses of 125 mm focal length and a beam splitter which reflects about 80% of the incident light. The lenses and one surface of the beam splitter are anti-reflection coated. All components are mounted for optimum mechanical stability and have tilt adjustments.

Lenses of various focal lengths and beam splitters of other reflectivities can be interchanged.

VI. Photographic Film Holder

The photographic film holder is designed to accommodate standard 4″ x 5″ photographic film. The holder is light tight when the dark slides are in. When making transmission holograms, only the dark slide on the object side need be pulled. On the other hand, when white light holograms are being made, both dark slides can be opened to allow light to reach the photoplate from both sides.

VII. Laser

The laser that accompanies the holography system is an integrated package of 4⅜″ x 5⅜″ x 22″ delivering a 2 mw uniphase beam at 6328 Å. It operates off the common 120 V. 60 Hz supply by a simple "on-off" switch. A smaller output is simultaneously accessible out of the opposite end of the laser and is useful for output monitoring.

Higher power output at multimode can be obtained by the adjustment of the three horizontal screws on each of the two external mirrors, which are accessible when the end plates are removed. These plates, as well as the top cover, can be removed without disturbing the laser alignment. However, physical contact with the plasma tube and the electrical leads inside must be avoided during operation, and care must be exercised in preventing the direct beam from entering the eye.

When used for holography, the laser can be operated on the rectangular bench (page 6) with the beam directed to the desired position by the beam deflector (page 6). Uniphase operation is necessary.

Experiments in Wavefront Reconstruction

Introduction

The basic ideas of holography were originated by Dennis Gabor in 1948 (1, 2, 3). With the advent of the laser and an improved process by Leith and Upatniek, (4, 5, 6, 7) it caught the excitement and imagination of the scientific world 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 device. Some major properties of holograms are as follows:

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 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 limited perspective and resolution.

3. More than one independent scene can be recorded on the same photoplate (7). 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. They can be encoded so that only the person in possession of a decoding device can see the true image (8).

5. Three dimensional multicolor scenes can be recorded holographically using the combined light of different colors from more than one laser (9, 10, 11, 12). The reconstruction can be performed using a point source of light from any thermal source, such as the sun or a tungsten filament light bulb, without the need of color filters.

6. Using a light from a pulsed laser, a bullet in flight plus its shock wave, can be captured holographically (13).

7. Objects undergoing very slight deformation which escapes any previous methods of detection can now be studied with a differential hologram (14), which essentially compares the image of an object at one time with the image at any other given time. Objects under steady state vibration with small amplitudes can also be studied in a similar manner (15).

8. A cylindrical hologram (16, 17) can be made which offers a 360 degree view 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 can reveal a

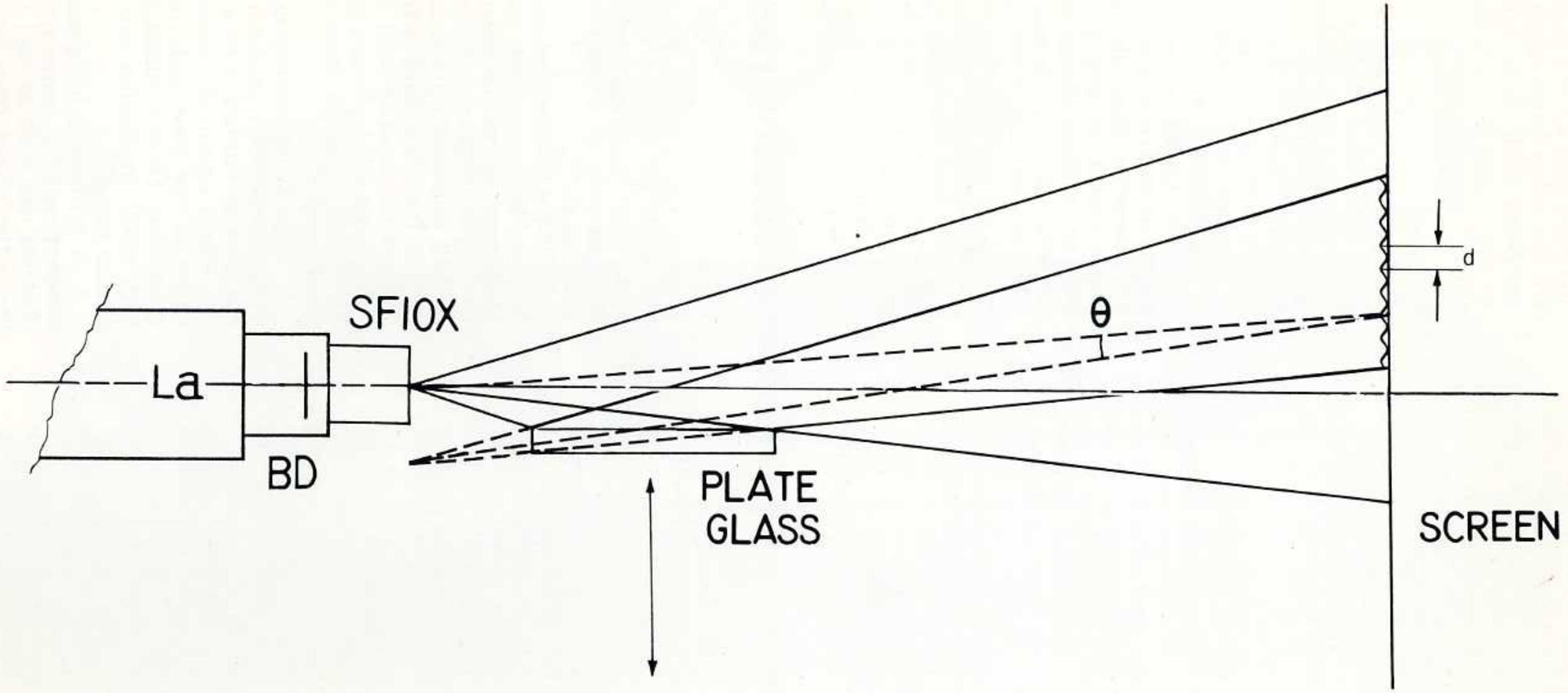


Figure I·1

completely independent scene, also in all perspectives.

9. Sound waves have been used to make holograms (18) which can be converted to optical holograms.

10. Extension of holographic techniques to include microscopy and X-ray studies are now under consideration (19).

These and many other attributes of holography make it a fruitful field for researchers and a stimulating laboratory experience for students.

Comprehensive works on the theortical foundation of holography (20, 21) are available. The purpose of this writing is not to duplicate or summarize them. The basic philosophy here is that holography is learned by making holograms.

There are three levels from which the following exercises can be approached. *First*, it is possible to merely follow the instructions and carry through the experiments, without consulting any of the references suggested. Enough experimental details are given to enable an amateur to pursue holography for fun or profit. *Second*, by studying the background reading footnoted, all of which is selected from popular texts at the elementary level, the experimenter will be able to understand the basic principles of holography. *Finally*, references to the scientific journals are given so that the subject can be pursued at the professional level.

The elementary texts to be cited and their abbreviated notations are listed below: (The subject matters referenced from them can also be found in other texts.)

Resnick and Halliday, *Physics*, John Wiley & Sons, Inc. (1966) (Will be referenced as R&H)

Sears and Zemansky, *University Physics*, Addison-Wesley (1964) (Will be referenced as S&Z)

Jenkins and White, *Fundamentals of Optics*, McGraw Hill (Third Edition) (1957) (Will be referenced as J&W)

The symbols used on the diagrams and their definitions are:

La — Laser
BD — Beam deflector
SF10X — Spatial Filter with a ten power microscope objective
BS80 — Beam splitter which reflects 80% of the incident light
M — First surface mirror
L-125 — Negative lens with a focal length of 125 mm
O — Object or scene to be holographed
G — Ground or opal glass
PH — Plate holder with photoplate, film, or hologram (or loaded camera back)

Laboratory Exercises

I. Hologram of Point Object at Infinity—Sine Grating

Before doing the actual experiment, set up the demonstration of a Lloyd's mirror (a, b) as shown in Fig. I.1. By moving the plate glass (or first surface mirror) up near the beam axis, the interference pattern formed between an actual point source and an apparent one (dotted lines) can be observed. This pattern is the same as one that would result from a Young's double slit experiment (c, d, e). A preliminary experiment can be done to show that the spatial frequency f, the number of cycles per unit length on the screen is:

$$f = \frac{1}{d} = \frac{\sin\theta}{\lambda}$$

where d is the distance between adjacent maxima or minima, θ the angle subtended by the rays from the two sources on the screen, and λ the wavelength of the light used.

By lowering the reflector, θ is increased and the fringe pattern on the screen gets finer. Continued increase in θ will cause the fringes to be so fine as to render them unobservable to the eyes. The mechanical stability of the system now becomes important. Any small relative movement between the mirror and the laser-spatial filter system will cause the fringes to be smeared.

In order to record the pattern on photographic emulsion, the screen can be replaced by a photographic plate with the emulsion side facing the light (or simply a loaded camera with the lens removed). The configuration shown in Fig. I.2 is suggested for high frequency fringes. A laser beam is split into two components and then recombined at an angle θ to one another on the photoplate PH. By changing θ but always keeping the distances BS-M_1-PH and BS-M_2-PH approximately equal (f, g, h), sine gratings of different frequencies can be made. (See Appendix I for a discussion of film choice and darkroom techniques.)

Fig. I.3 (a) shows schematically the construction process. We shall arbitrarily call the direct beam the reference beam and the other the object beam. It should be realized that if the object beam had come from the direction as indicated by the dotted lines, the interference pattern would not be significantly changed, assuming that the emulsion is very thin. More will be said about this later.

After the exposed film is processed, its diffraction pattern can be studied by sending an undiverged beam directly from a laser through it and then onto a screen. It will be observed that the diffraction pattern consists of an undeviated beam (called the "dc" component) (i) and one diffracted beam on each side. In effect, the original object beam is being reconstructed. We have, in effect, a hologram of a point located far away. (See Fig. I.3 (b).)

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a. S&Z pp. 904
b. J&W pp. 242-3
c. S&Z pp. 898-900
d. H&R pp. 1068-1074
e. J&W pp. 234-239
f. S&Z pp. 895-897
g. R&H pp. 1074-1077
h. J&W pp. 243-4, 251-253
i. If the object beam had been parallel to the reference beam, i.e., $\theta = 0$, there would have been no fringes.

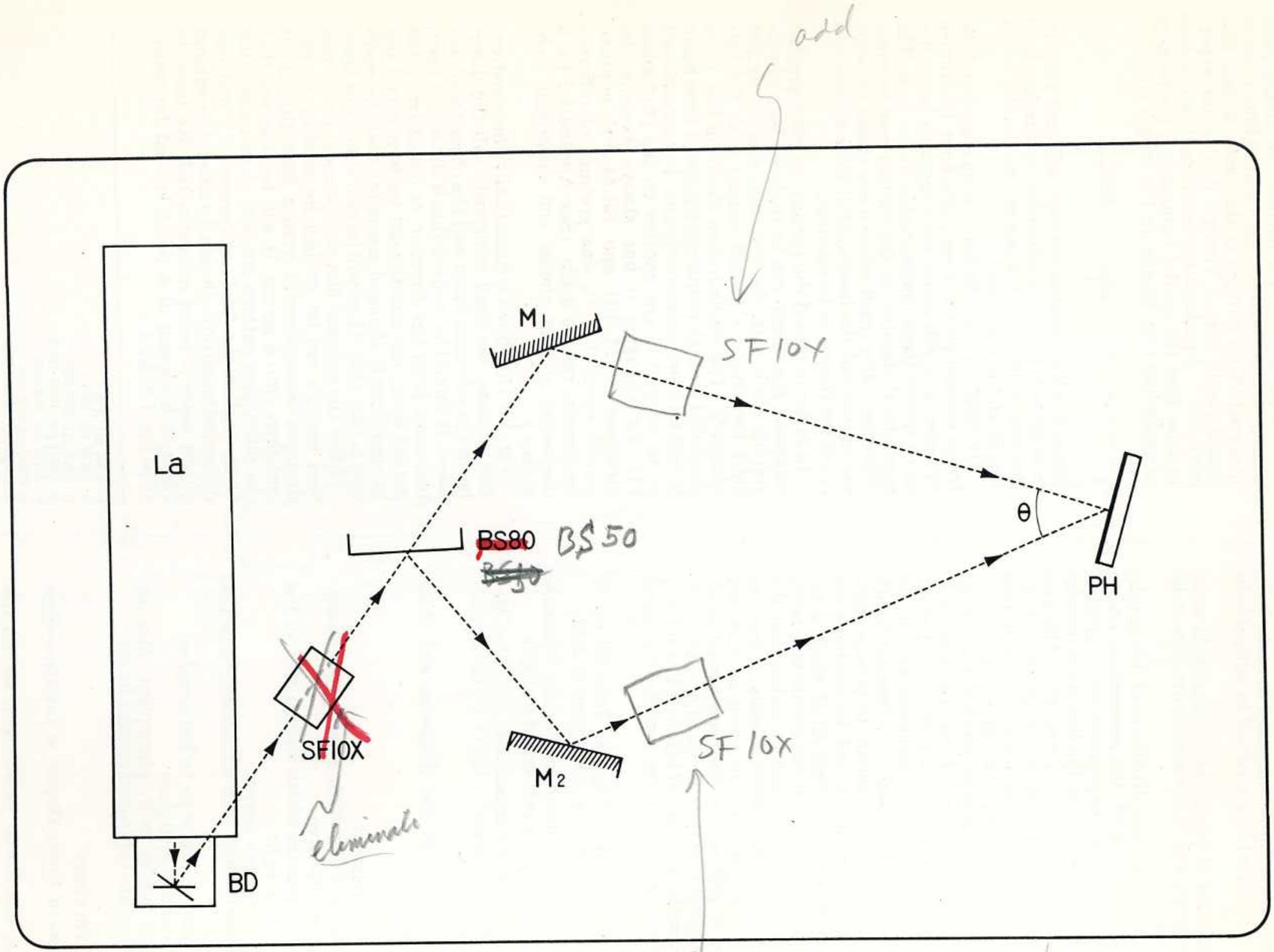

add
M1
SF10X
La
θ
~~BS80~~ BS50
~~BS50~~
PH
SF10X
eliminate
M2
SF10X
BD

Figure I·2

add

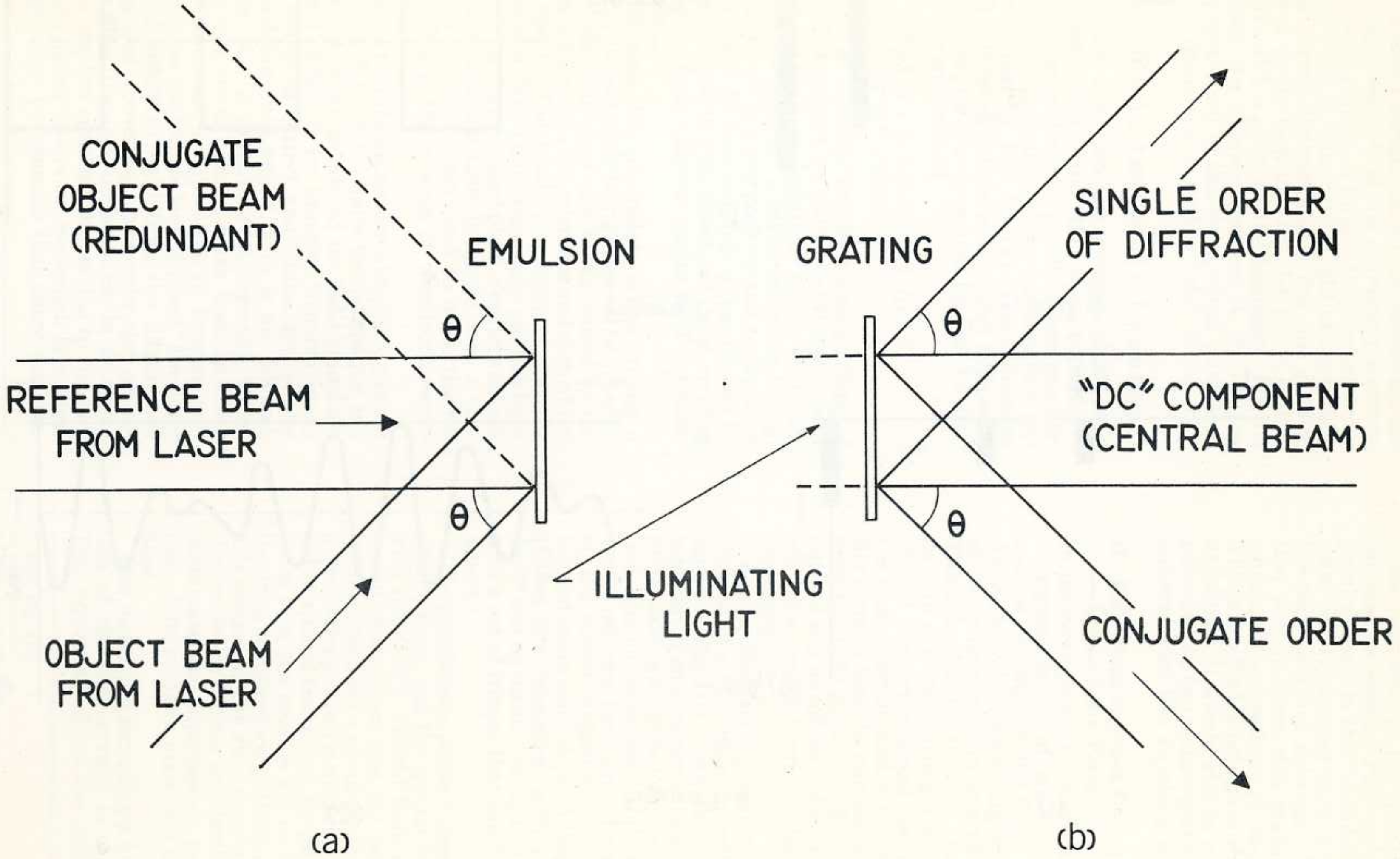
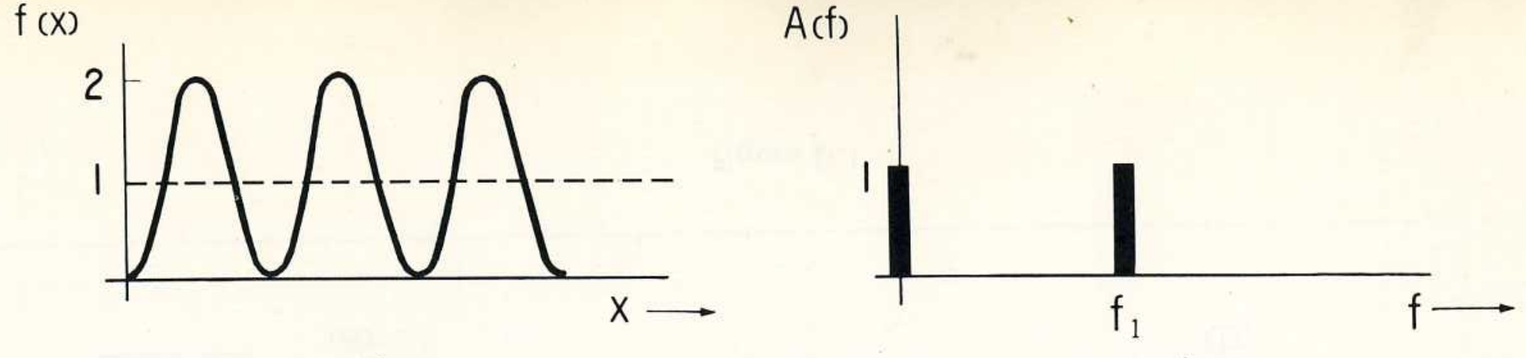
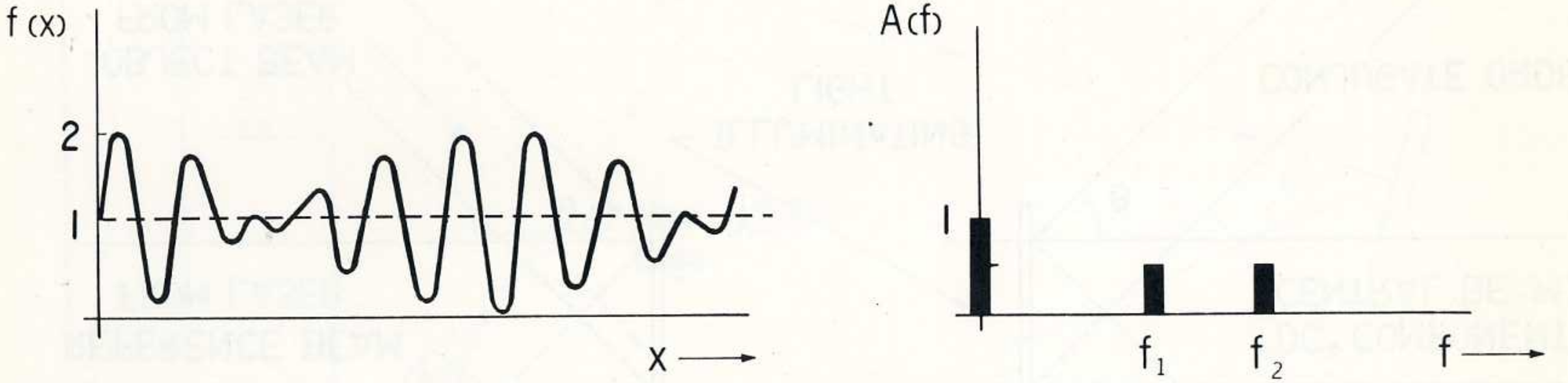

CONJUGATE
OBJECT BEAM
(REDUNDANT)
EMULSION
θ
REFERENCE BEAM
FROM LASER
θ
OBJECT BEAM
FROM LASER
(a)
GRATING
θ
SINGLE ORDER
OF DIFFRACTION
"DC" COMPONENT
(CENTRAL BEAM)
θ
ILLUMINATING
LIGHT
CONJUGATE ORDER
(b)

Figure I·3



(a) (b)

Figure I·4



(a) (b)

Figure I·5

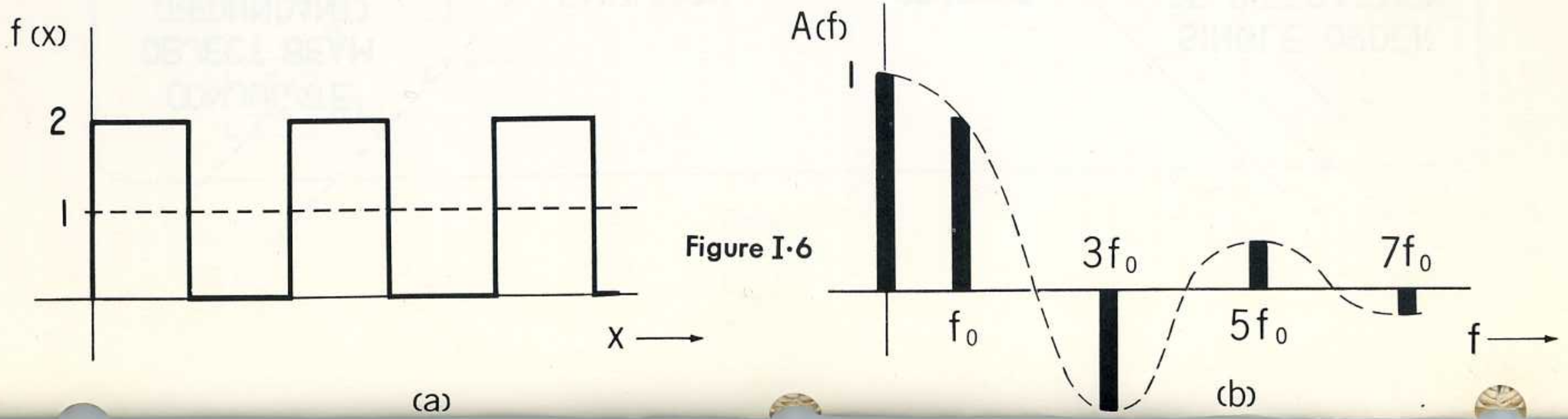


Figure I·6

The basic principle illustrated here is that the Fraunhofer diffraction pattern represents the Fourier analysis (j, k) of the diffracting aperture, in this case a grating. If we plot the transmittance f(x) (fraction of illuminating light energy transmitted) versus distance across the sine grating, the curve would look like Fig. I.4 (a) — a pure sine wave with a given spatial frequency. Fig. I.4 (b) shows the Fourier spectrum A (f) (or frequency spectrum) of this wave, which consists of a single frequency f_1 and a "dc" term. Analytically,

$$f(x) = A(0) + A(f_1) \sin (2\pi f_1 x) = 1 + \sin (2\pi f_1 x)$$

If we now take two sine gratings of different frequencies f_1 and f_2 and stack them together so that the fringe systems are parallel to one another, the transmittance curve of the combination will be represented by Fig. I.5 (a). The diffraction pattern will consist of the sum of that from each grating alone, or as represented by Fig. I.5 (b), the Fourier spectrum of

$$f(x) = 1 + A(f_1) \sin (2\pi f_1 x) + A(f_2) \sin (2\pi f_2 x)$$

Instead of stacking together sine gratings of different frequencies, we could have superimposed them on the same photoplate by double exposure, i.e., after the exposure is made according to Fig. I.2, M_2 is moved to a new position and an exposure is made again. In fact, multiple exposures can be made, each time having the object beam arriving at the plate from different angles with the reference beam.

In this case, the photoplate 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 each of the object beams. The result is a complex periodic wave pattern. When monochromatic parallel light is incident on the processed plate, Fourier analysis 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.

It follows that if a square wave intensity pattern as shown in Fig. I.6 (a) (alternating opaque and transparent bars) is desired on the photoplate, one could obtain it by bringing together many object beams of correct amplitudes and phases from predetermined angles. This is not advised. An easier way is to make a photographic transparency of a set of parallel black lines on white paper. The latter is equivalent to Fourier synthesis because the camera lens "gathers" the lower diffracted orders of light from the illuminated drawing and converges them onto the photographic film. The lack of resolution in a camera due to a smaller aperture stop is due to the fact that more higher orders are neglected. It is these high frequency components that carry the "details" of a picture. In other words, a lens acts as a low pass filter in the spatial domain of a communication system. The equivalence in the temporal domain is the "rounding off" of a square-wave electrical signal when it is passed through a low pass electrical network. The familiar diffraction pattern from this grating then shows the square of the spectrum of this wave Fig. I.6 (b). This is, in effect, a hologram of many point objects at infinity. It should also be realized now that, in principle, we can make a grating whose diffraction pattern looks like anything we wish.

II. Hologram of Point Object at Finite Distance —Gabor Zone Plate

In the preceding experiment, the recording plane is approximately of equal distances from the sources of coherent light (all of which are far). All the wavefronts arriving at the photoplate are of the same curvature, approaching plane waves. This accounts for the fact that the interference pattern is a set of straight lines, and of constant spatial frequency across the plate. If, however, the sources are located at different distances from the plate so that the curvatures of the wavefronts arriving at the plate are different, the interference pattern will no longer consist of straight lines nor will the sinusoidal variation be of constant spatial frequency(l).

As a preliminary experiment, set up the demonstration of a Michelson Interferometer (m, n, o) as shown in Fig. II.1. Note that M_1 is fixed while M_2 is mounted on a magnetic base with travel. A useful technique for initial alignment is to use a positive lens as indicated, so that each of the two beams reflected back from the mirrors are focused on the screen. Adjust the mirrors until the two focused spots coincide, and then remove the lens. (Other interferometers such as the Mach-Zehnder(p) can be readily set up and demonstrated, all with a set of fringes that can be projected onto a screen.)

The interference pattern consists of a set of concentric rings, and the spatial frequency increases with radius (22). Viewed from the locality of the screen on the beam axis, the two light sources can be considered to be along the line of sight, and the interference pattern is made up of concentric rings of low spatial frequency. As we go away from the beam axis, the sources are no longer in line, and the local interference pattern consists of an off-axis section of the ring system. We can imagine that as we go farther and farther away from the beam axis, the interference pattern approaches that of the previous exercise, i.e., parallel straight lines.

One method of recording a high frequency section of this ring system is shown in Fig. II.2. This system simulates two point sources located

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j. R&H pp. 470-472
k. J&W pp. 211-223
l. S&Z Fig. 41-2
m. S&Z pp. 905
n. R&H pp. 1090-1092
o. J&W pp. 244-250
p. J&W pp. 257

— means eliminate

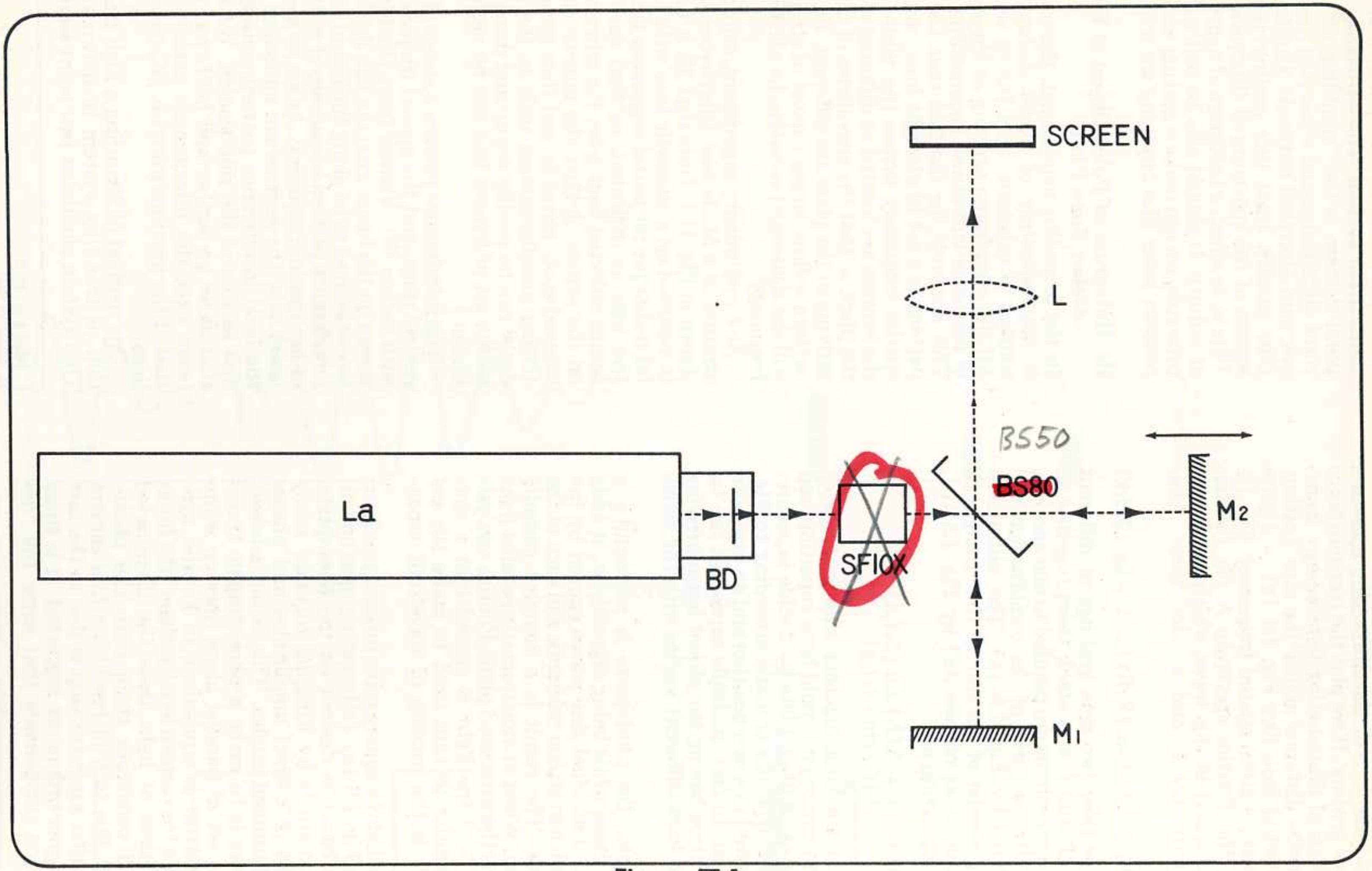

Figure II·1

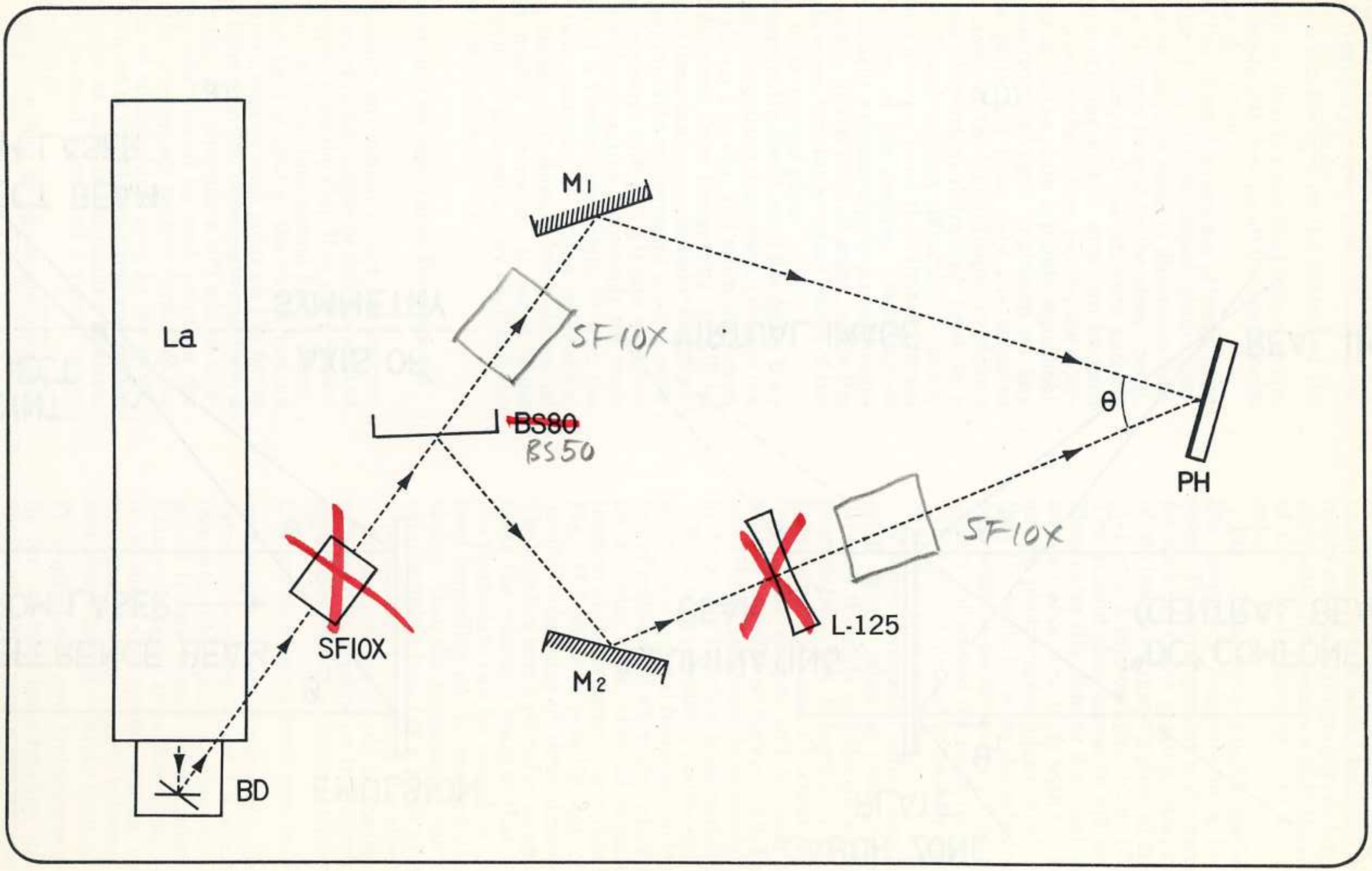

Figure II·2

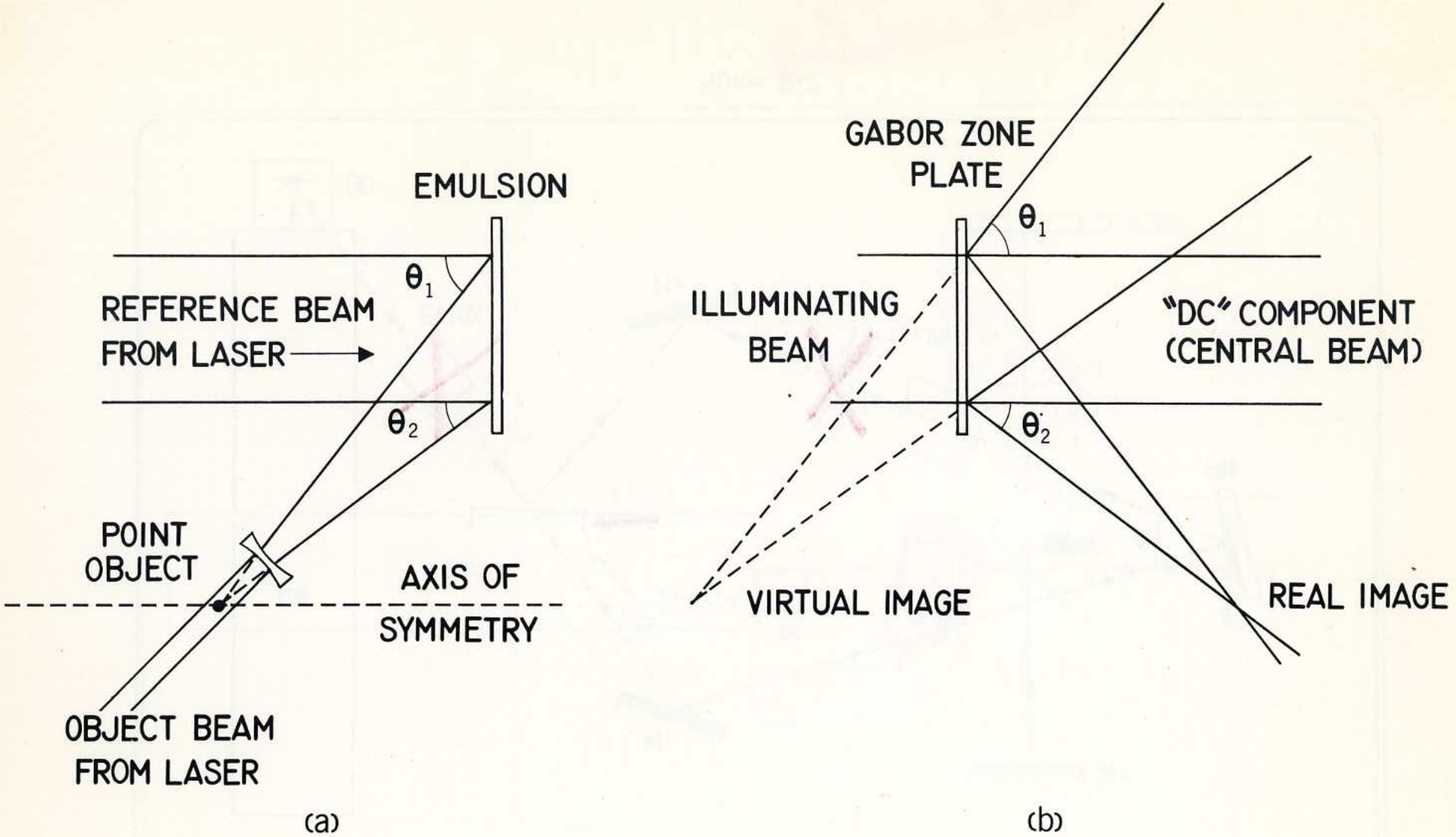
EMULSION
θ1
REFERENCE BEAM
FROM LASER
θ2
POINT
OBJECT
AXIS OF
SYMMETRY
OBJECT BEAM
FROM LASER
(a)
GABOR ZONE
PLATE
θ1
ILLUMINATING
BEAM
"DC" COMPONENT
(CENTRAL BEAM)
θ2
VIRTUAL IMAGE
REAL IMAGE
(b)

Figure II·3

at different distances and off-axis from the recording plane. Using Fig. II.3 (a) as a schematic representation of our system, it can be seen that the spatial frequency varies continuously from $\frac{\sin \Theta_1}{\lambda}$ on the top to $\frac{\sin \Theta_2}{\lambda}$ on the bottom of the plate. We can say that our recorded fringe system subtends a *bandwidth*, having all the frequencies between the above two.

Fig. II.3 (b) shows the process of wave front reconstruction from the developed plate. Consider an area on the plate small in dimension compared to the distance from it to the object point. During the exposure, both the reference and the object beams arriving at this area can be each considered to be parallel. Thus, *locally*, the interference pattern on the plate is purely sinusoidal. During reconstruction, light impinging on any part of the plate 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 the grating diverges more than that diffracted from the bottom of the grating. Thus, half of the diffracted light will converge to a point, forming a real image of the original point, while the other half diverges, forming a virtual image of the same point at its original place.

To demonstrate the result, send the direct laser beam through the grating thus made. Observe the diffracted light on a screen, and move the screen to various distances from the grating. It will be observed that there is always one order of diffraction only, but one side converges to a point while the other side always diverges. (It can be noted here that the above grating is precisely the same as a section of a Fresnel zone plate (q) with the exception that instead of having alternating opaque and transparent rings, it has a sinusoidal variation in opacity with radius. In honor of the original inventor of holography, we shall call the grating the Gabor zone plate.)

III. Hologram of Two and Three Dimensional Scenes

Photographically, any actual object can be considered as a set of point sources of light located at various distances from the film. If in our previous exercise a two or three dimensional figure illuminated by laser light is used as the object instead of a single point source, each point on the figure will scatter light onto the photoplate and form a system of rings. The photoplate will add or integrate all the sets formed by each point on the figure, 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 at each corresponding location, thus creating in total a real and a virtual image of the entire figure.

If high resolution film or plates are available, our very next step can be the holographic recording of a three dimensional scene. However, if they are not available, holograms can still be made using readily available black and white film ordinarily used in photography, so long as we confine our spatial frequencies within the resolution limits of the film by limiting Θ to a sufficiently small value.

Fig. III.1 shows a possible method of making a low frequency hologram of a two dimensional scene. The arrangement is the same as that used for making a sine grating, except that into one of the beams we insert a piece of fine ground glass (G) and a photographic slide (O) taped to it. The ground glass serves to diffuse the light and illuminates the slide so that each point on it will form a Gabor zone plate with the reference beam on the photographic plate. Again, make certain that the angle between the reference and the object beam is minimized, so that no spatial frequency will exceed the resolution of the emulsion. (This is one method of measuring the resolution limit of a given emulsion.)

A three dimension effect can be achieved if small objects (such as chess pieces) are placed between the slide and the photoplate. In the reconstruction, the hologram is viewed by laser light from the same direction as the reference beam. The objects will be seen as silhouettes against the slide as background. In all cases, observe the correct beam intensity ratio as discussed in Appendix I during hologram construction.

With high resolution plates, one hardly has to worry about spatial frequency so long as the problem of mechanical vibration, which can be caused by acoustic noise, thermal expansion and contraction of the apparatus, is avoided. In this case, Fig. III.2 shows a possible way of making high quality holograms of three dimensional objects. The negative lens is placed at an appropriate point along the reference beam so that its intensity on the photoplate can be varied to the appropriate level depending on the amount of light from the object. Also, the illumination can be spread out, using another lens (or a piece of ground glass), depending on the size of the object.

At this point it should be mentioned that light rays from each point on the object interfere with each other, forming spurious fringes with spatial frequencies varying from zero to $\frac{\sin \phi}{\lambda}$ cycles per unit length. Here ϕ is the angle subtended by the extremities of the object (or scene) on the surface of the photoplate. During reconstruction, this set of fringes causes a background "noise". To isolate the signal from this noise, we merely need to arrange the system during construction so that the minimum angle between the reference and object beams, is larger than ϕ.

IV. Multiplexed and Multichanneled Holograms

So far, we have been treating the photographic emulsion as if it were a two dimensional medium. The resulting holograms were regarded as having spatial frequencies in only two dimensions — x and

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q. J&W pp. 360-1

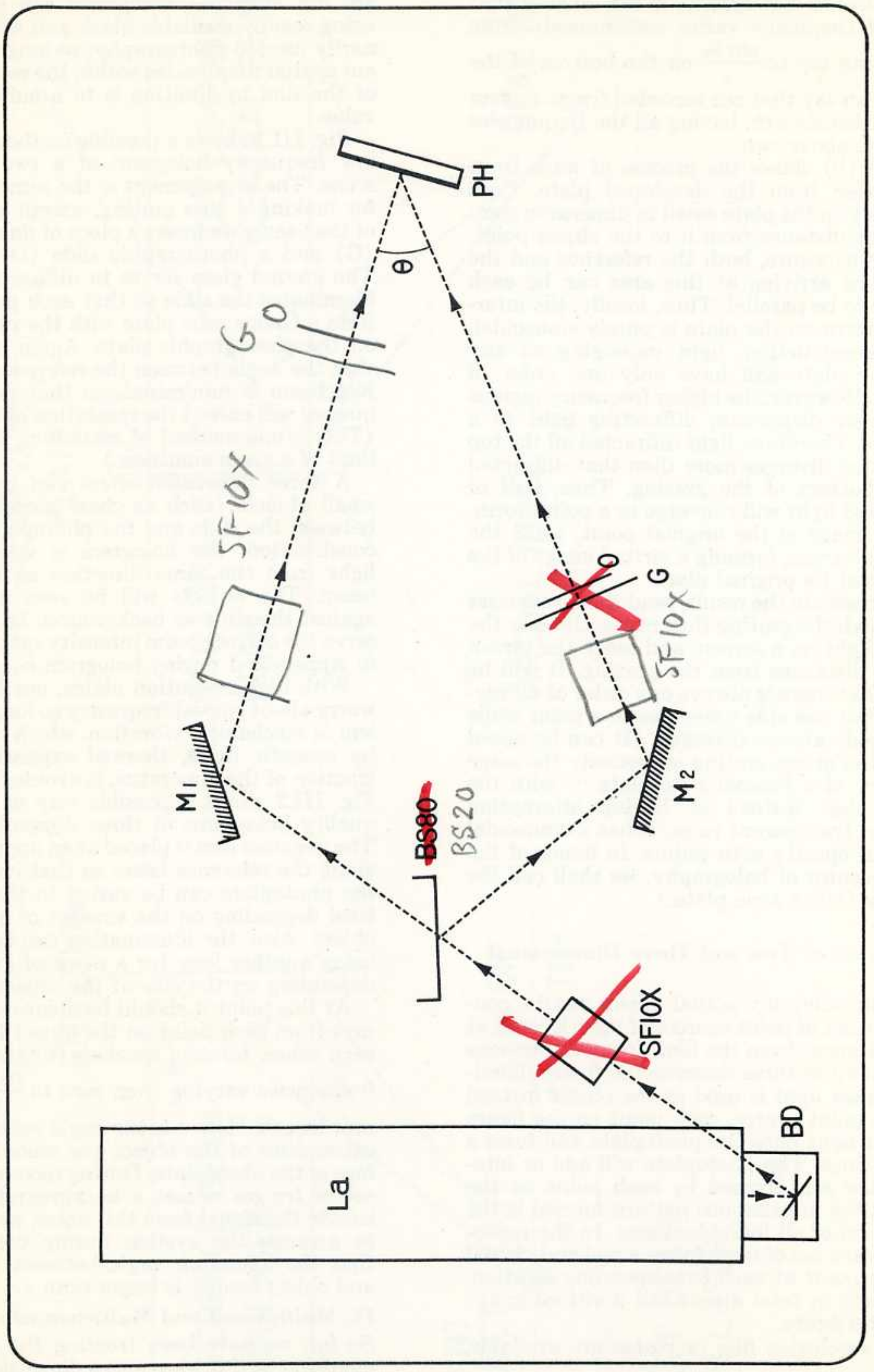

Figure III·1

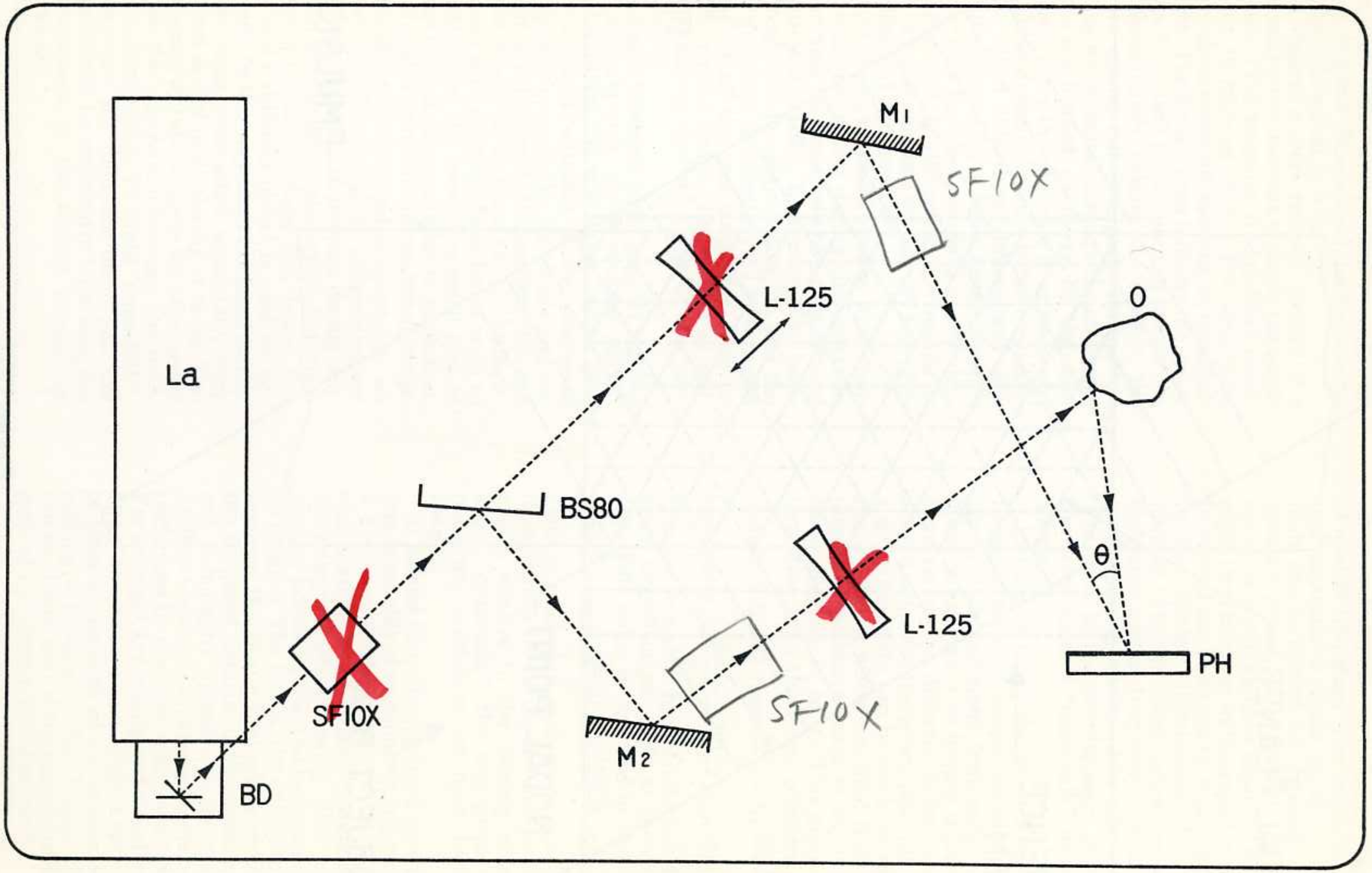

Figure III·2

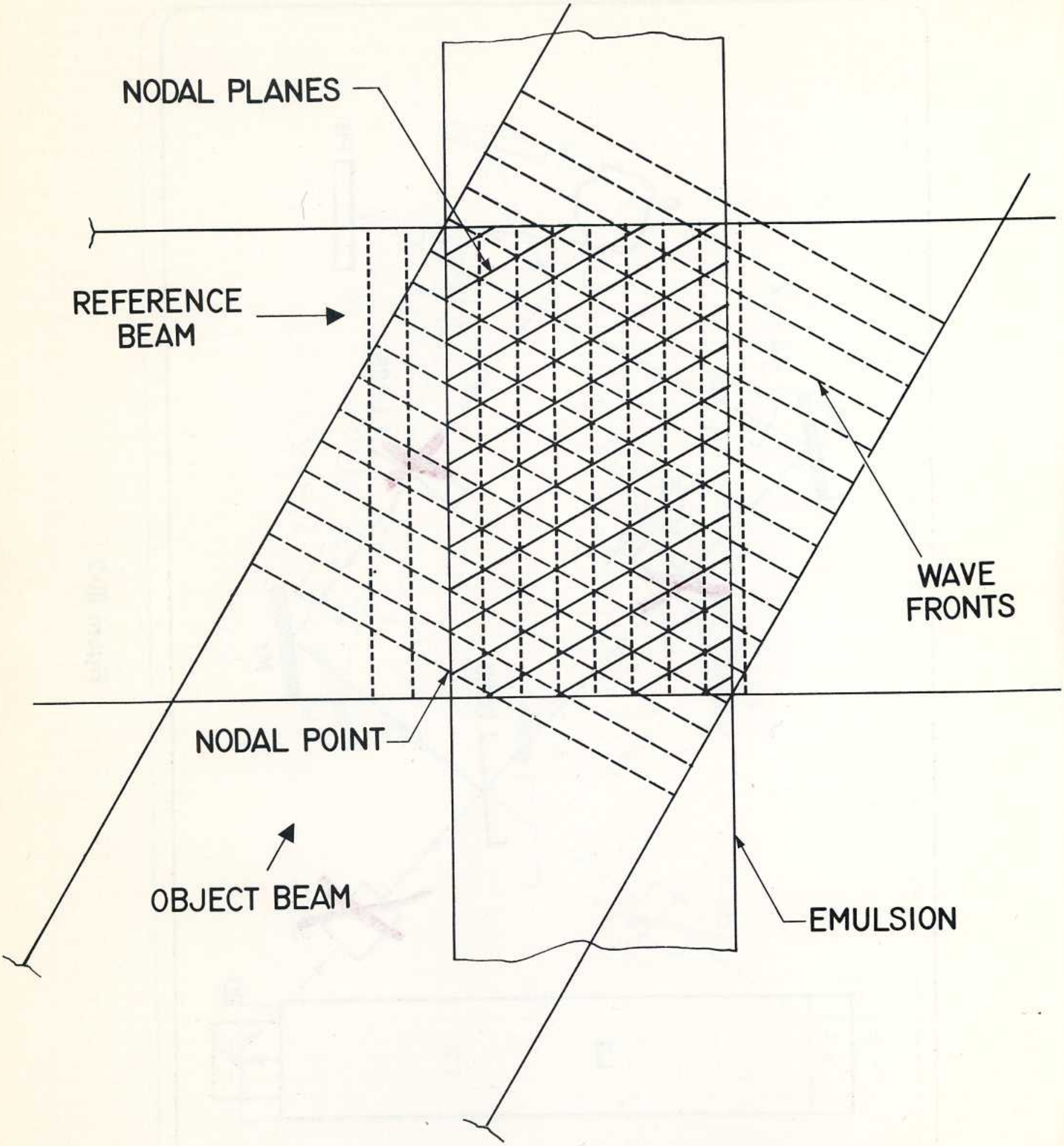
NODAL PLANES
REFERENCE BEAM
WAVE FRONTS
NODAL POINT
OBJECT BEAM
EMULSION

Figure IV·1

y. The fact, of course, is that the thickness of the emulsion is finite, and varies from a few to tens of microns. The diffraction pattern recorded on it, therefore, is three dimensional, having a component in the z direction as well.

Fig. IV.1 depicts a more realistic picture of a hologram construction because it shows the emulsion thickness. (For example, Kodak 649F emulsion is about 16 microns thick.) For simplicity, consider two plane waves intersecting on the emulsion as shown. The dotted lines indicate the crests of the waves from each of two parallel beams. 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 solid diagonal lines. After the emulsion is exposed and processed, these darkened planes behave as venetian blinds. When this three dimensional sine grating is illuminated by a laser beam, the diffracted order that travels upwards is unimpeded, but the order that is diffracted downwards is "shut off". In radio parlance we can call this phenomenon sideband suppression(r).

If the point object is substituted by light from a three dimensional object during the construction, the resulting hologram will be a complicated three dimensional grating. In viewing, the hologram is relocated to its original position and the reference beam alone illuminates it. The venetian blinds will shut off the real image but have no effect on the virtual image. The degree of suppression depends on the thickness of the processed emulsion.

The real image, however, is not lost. By turning the hologram *backwards*, which reverses the direction of the blinds, the real image can be projected onto a screen situated at the conjugate position originally occupied by the object and the virtual image is suppressed. In practice, this can be done more effectively by illuminating the backward hologram with a narrow laser beam, such as comes directly from the laser. The small spot of the hologram used causes a sacrifice in resolution, but depth of field is gained in the projected image.

Using the effect of sideband suppression, we can now record different sets of information on each of the two sidebands. In practice during construction, the once exposed photoplate is turned upside down with the emulsion still facing the object side, and a different object is used for another exposure. In this way, each sideband can be said to have been modulated separately, very much the same as FM multiplexing in radio. The finished hologram will show one or the other scene depending on the orientation between the hologram and 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 objects should be sufficiently small.

More than two scenes can be recorded and viewed one at a time on the same photoplate, with all the information recorded in the same interval of spatial frequency. For example, after the second exposure is made as described above, the plate can be turned 90° exposed once more with another object, then turned 180° and exposed again with still another object. The process hologram then has four independent scenes which can be viewed one at a time by rotating it with respect to the viewing illumination. In principle, any number of independent scenes can be recorded on the same spatial frequency region by making a small rotation on the plate after each exposure. The limit is the overexposure of the plate and the occurrence of "cross-talk" between adjacent scenes.

Instead of using the same frequency interval to record separate scenes, we can also make holograms using different frequency intervals. The latter is analogous to having different radio stations occupying different finite bandwidths over a large temporal frequency interval. For example, a given exposure can be made as represented by Fig. IV.2 (a), where the light from the object O meets the reference beam at angles varying continuously from Θ_1 to Θ_2. This means that the information from this scene occupies a spatial frequency interval from $\frac{\sin\Theta_2}{\lambda}$ to $\frac{\sin\Theta_1}{\lambda}$ and has a bandwidth of $\frac{\sin\Theta_2}{\lambda}-\frac{\sin\Theta_1}{\lambda}$. Another scene O′ can now be recorded by introducing the reference beam from a larger angle as shown in Fig. IV.2 (b). This scene is recorded in the frequency interval between $\frac{\sin\Theta_1'}{\lambda}$ and $\frac{\sin\Theta_2'}{\lambda}$. After the exposed plate is processed, each scene can be viewed independently by tilting the hologram to different angles relative to the viewing illumination. To avoid "cross-talk", the two frequency intervals must not overlap or we must have Θ_1' greater than Θ_2.

It should be quite apparent now that this system is capable of accommodating more "stations" if the bandwidth of each of them is small; and each station can be "dialed", literally, by turning the hologram when viewing. The rather striking analogy between radio and holography should now be realized. The fact is, the only formal difference between the two is that while radio operates in the temporal domain of the communication theory, holography operates in the spatial domain. Endless amount of experiments analogous to those performed by electrical engineers can be pursued. For example, try coding and decoding by "scrambling" the "carrier", i.e., place a very warped piece of glass in the path of the reference beam while making a hologram (Fig. III.2). The hologram can be viewed only if the same glass is used in the path of the viewing illumination(8).

V. White Light Holograms

Referring back to Fig. IV.1, we see that the nodal

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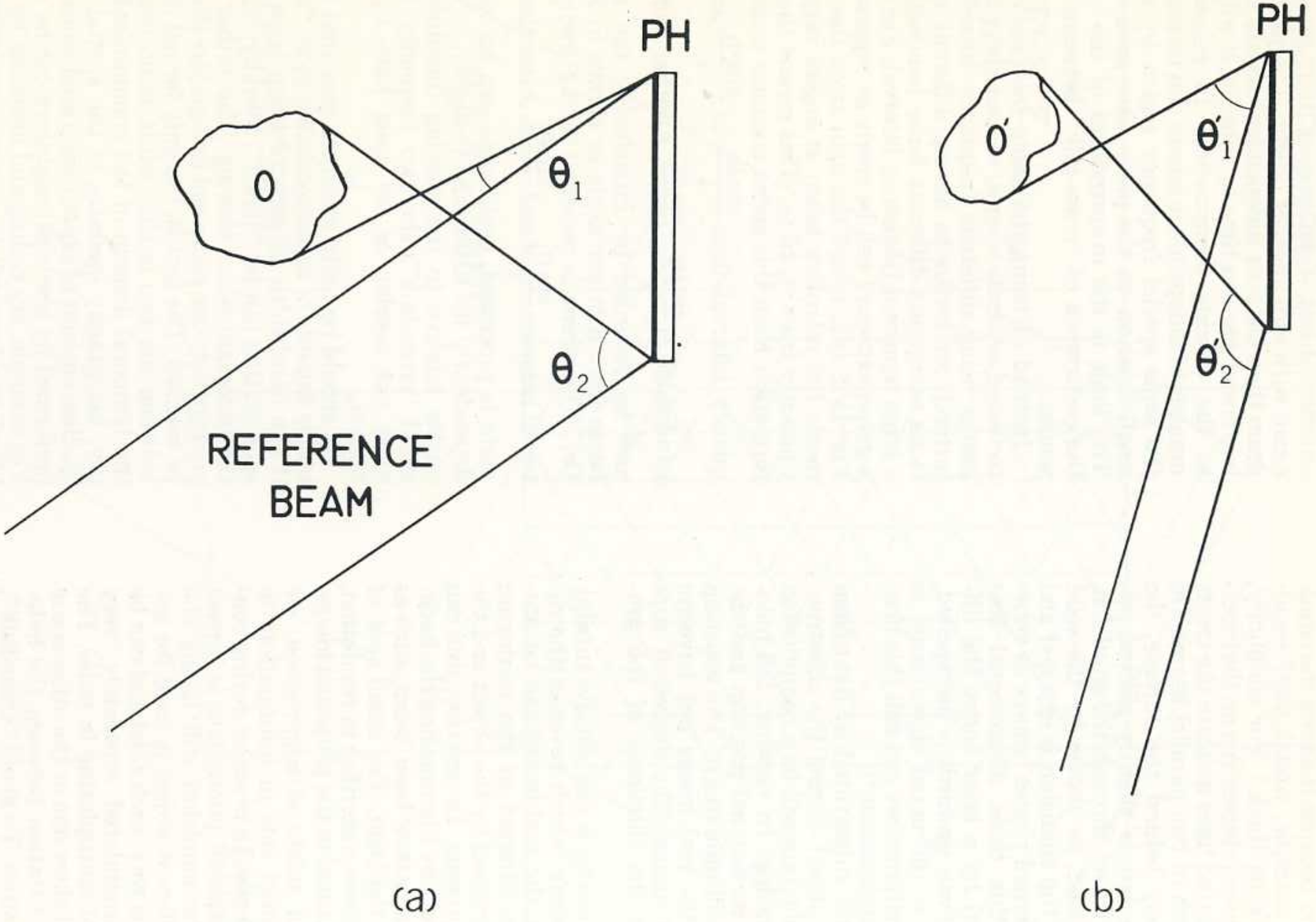
[r] The preceding description is a simplified one based on geometric optics. For a general and more sophisticated treatment, see reference 23.



(a)

(b)

Figure IV·2

planes formed by two traveling waves through the emulsion lie along the angle bisector of the waves. If the two waves approach the plane of the emulsion perpendicularly from opposite sides, the nodal planes thus formed would be parallel to the plate. The separation between planes would be $\frac{\lambda}{2}$. In fact, the first demonstration of standing light waves was performed in 1890 by Wiener, who sent a beam of light through a photographic emulsion and then reflected it back from the other side with a mirror. The developed emulsion showed the locations of the nodal planes. In 1891, Lippmann used the same phenomenon to record on black and white photographic emulsion a multicolor picture and subsequently won a Nobel Prize in physics in 1908.

We shall use this fact to construct holograms (9, 10, 11, 12) which can be viewed with a point source of incoherent light such as that directly from the sun or from an unfiltered tungsten filament light bulb.

Consider the configuration shown in Fig. V.1. The object and the reference beams approach the emulsion from opposite sides, forming standing wave patterns into, as well as, across the emulsion. Since the high resolution emulsion is typically very thick (about 16 microns for Kodak 649F) and the wavelength of the light used is short in comparison (0.6 microns for He-Ne laser), many nodal planes are formed in the emulsion. After processing, the hologram behaves like a crystal, and undergoes the equivalence of Bragg diffraction(s) when illuminated by white light from the direction of the original reference beam. The image is seen at the original position of the object. 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 can be varied slightly by moving the white light source to a different angle of incidence, or by changing the temperature of the hologram which changes the spacing between planes, and the index of refraction. Usually, the emulsion shrinks slightly during the processing, and the color of the reconstructed image is shifted to a higher frequency, so that if the construction is made in red light, the reconstructed image will be green. The problem can be remedied to a degree by soaking the finished hologram in triethanolamine $N(CH_2\,CH_2\,OH)_3$.

If both Argon and He-Ne lasers are available, their light can be combined to make a hologram in multiple colors(12), also reconstructible in incoherent white light. Here, each color interferes with itself and not with the other colors, and creates an independent set of three dimensional interference patterns. The hologram then behaves as a multiple resonant system. When impinged by white light, which can be considered as electromagnetic noise with all the visible frequencies, only a few discrete frequencies will be reflected coherently.

VI. Differential Holograms for Vibration and Stress Analysis

From the previous discussions, we have given the impression that *nothing* can move during hologram construction. This is not always true.

If a Q-switched ruby laser is used instead of a continuous wave He-Ne laser, the completed exposure for a hologram is made in a matter of nanoseconds. Under this circumstance, even a bullet in flight can be holographed(13).

Objects undergoing steady state vibration, however, can be holographed with a continuous wave laser (15). In this case, we can consider the finished hologram as having been exposed many times. The nodal lines of the vibrating object do not move and will appear as illuminated areas of the object; on the other hand, the antinodes move throughout the exposure and the interference pattern caused by light from these areas and the reference beam are smeared out, so that in the reconstruction, these areas appear as dark fringes.

Continuous wave holography can also be applied to strain analysis(14). Suppose it is desired to study the magnitude and direction of displacement of every point on an object's surface when a load is applied. Fig. III.2 can be used to make an exposure without the load. The load is then applied, and another exposure made and then the plate is processed. We have then a doubly exposed hologram. During reconstruction, we see both images at once – one before and one after the load is applied. The two images will interfere with one another and fringes will appear across the surface.

This technique can also be used for real time studies. Basically, we wish to compare the image of an object at a given time with the actual object at any other time. This can be done by making a singly exposed hologram, placing it back precisely to the position during exposure, and view the reconstructed image by the original reference beam. The object is still illuminated by the laser, and will be seen in register with the image. If any part of the object has been displaced, the light from it will cause interference with the image from the hologram and fringes can be seen on the object. The most difficult part of this experiment is the precise reposition of the processed hologram(14).

It should be mentioned that phase objects invisible to the eyes can also be holographed and rendered visible in the reconstruction. For example, a transparent object, when placed in the position of G and O in Fig. III.1 would distort the wavefronts of the object beam, and the resultant interference fringes recorded will contain all the information concerning the distortion. If now the phase object is removed, and a hologram is exposed again to the empty volume(24), a plane sine grating is formed between the plane waves

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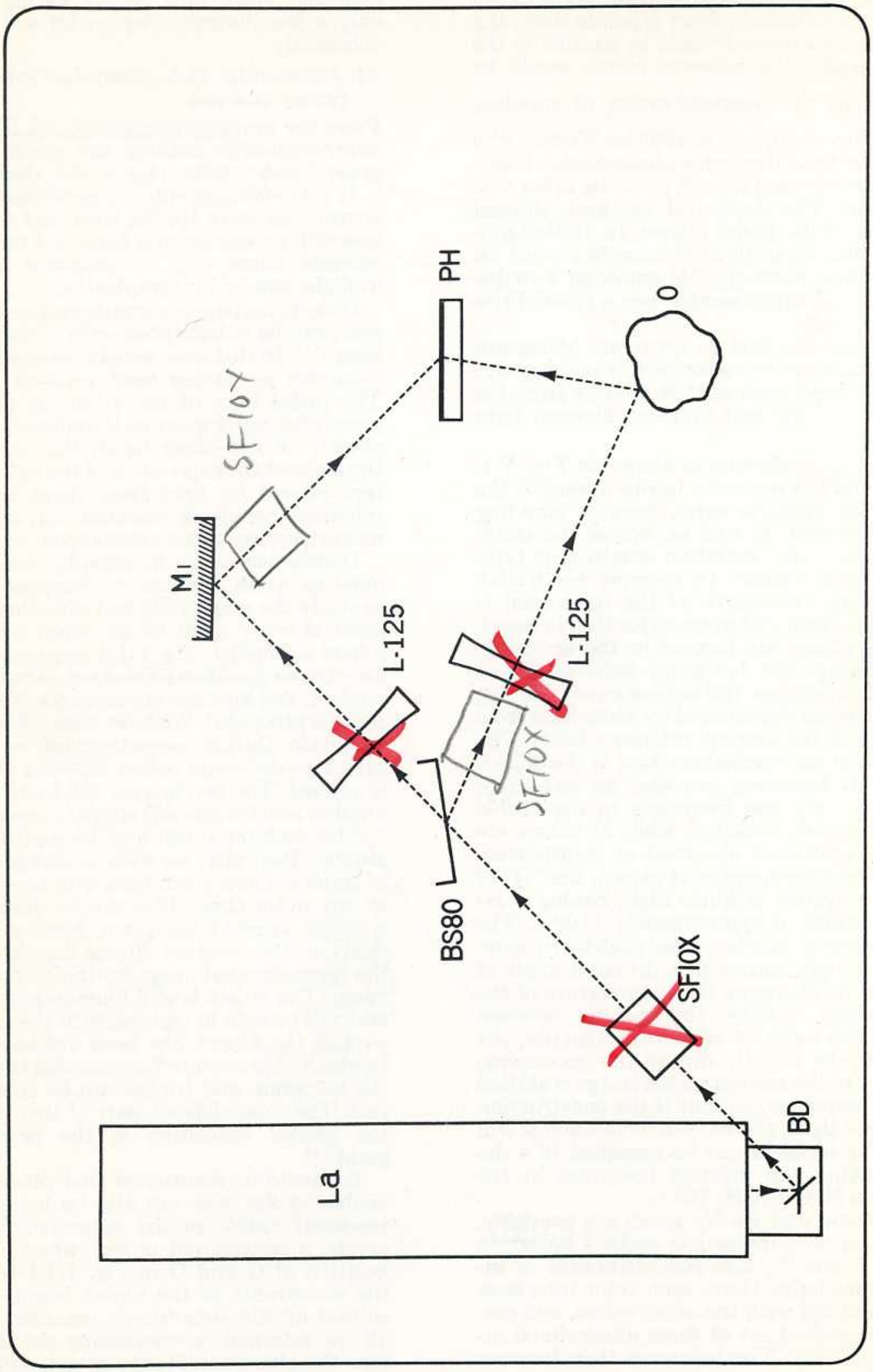

Figure V·1

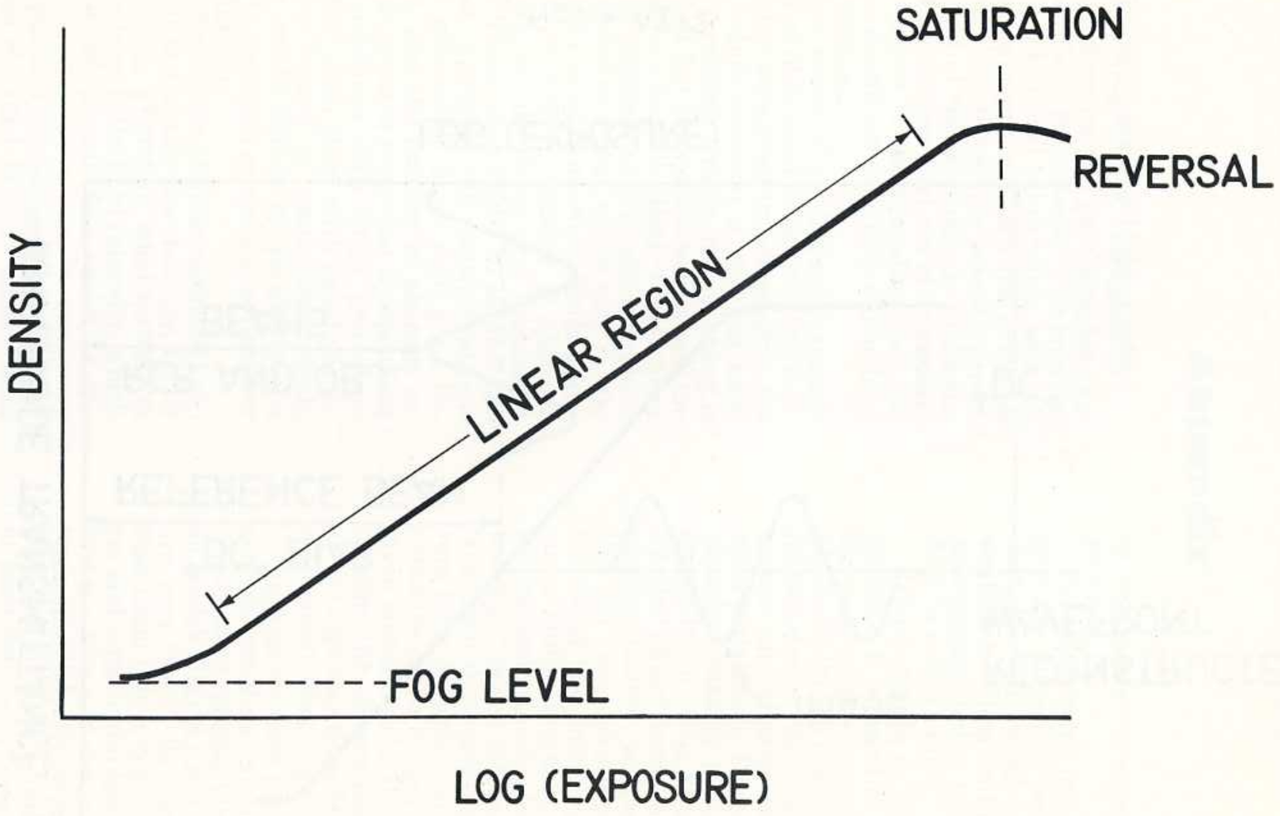
SATURATION
REVERSAL
DENSITY
LINEAR REGION
FOG LEVEL
LOG (EXPOSURE)

Figure AI·1

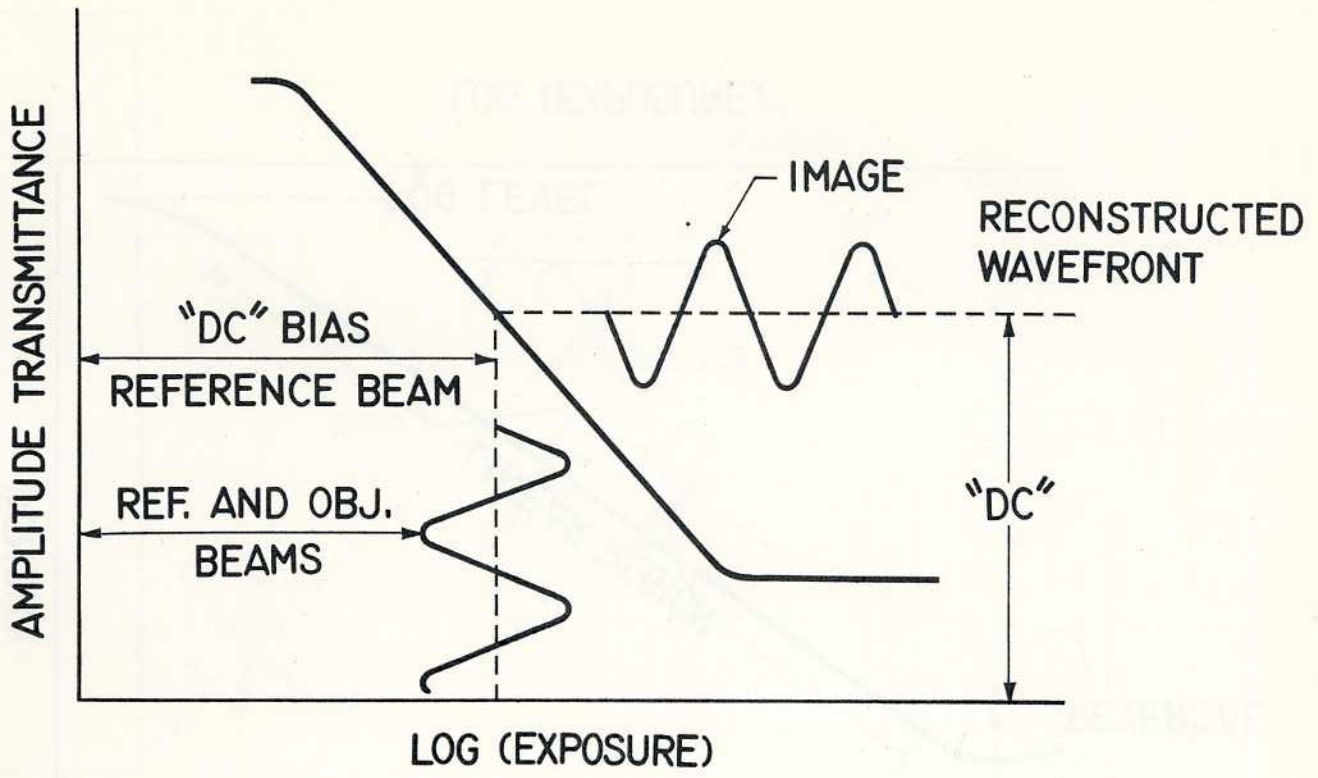
AMPLITUDE TRANSMITTANCE
"DC" BIAS
REFERENCE BEAM
REF. AND OBJ.
BEAMS
IMAGE
RECONSTRUCTED
WAVEFRONT
"DC"
LOG (EXPOSURE)

Figure AI·2

of the object and the reference beams. The resultant reconstruction from the hologram yields the interference between a reconstructed plane wave and a distorted wave, and the phase object is seen as an amplitude object.

An even more interesting extension(24) of this technique is as follows: Holograph only the empty volume, precisely reposition the processed sine grating, and then put a phase object into the object beam. This object can then be seen in real time. Thus, the object can be a transparent wind tunnel with air foil, heat from a hand, or any transparent and transient event that somehow distort the index of refraction in the path of the object beam. As before, what one sees is the interference pattern between a plane wave reconstructed from the sine grating and the distorted wave from the object.

Appendix

I. Dark Room Techniques For Holography

Complete information on the photographic process is readily available in textbook(25) or encyclopedic forms(26). Additional information with regard to any particular products are also available by request from their respective manufacturers. The chief function of this appendix is to discuss some ideas and procedures that are of immediate necessity with respect to the preceding test, but not to enable the experimenter to fully understand the chemistry involved.

Although other forms of photographic recording media, such as photochromic glass(27) or thermoplastics(28) have been used in holography, the familiar silver halide emulsion is still the most versatile and convenient. Briefly, the emulsion is a mixture of silver halide crystals with a gelatin, deposited either on a flexible plastic film or glass backing (plate or photoplate). The photosensitive material is deposited in *grains,* which vary in size from a fraction to several microns. Each grain, upon absorption of a given number of photons, will interact with the developer and becomes a darkened spot. Those that failed to absorb the required number of photons will remain transparent throughout processing. Since each grain behaves as a unit, and the number of photons required for development is somewhat independent of grain size, emulsions with larger grains are said to be "faster" than those with small grains. The trade-off for "speed" is "resolution" which, for our purpose, can be defined as the ability of a given emulsion to distinctly record a given number of lines per millimeter.

One important attribute of the emulsion to keep in mind is that it is a square-law detector, i.e., it is totally integrating. Therefore, what matters in exposing the emulsion is the light intensity, which is the square of the electric field vector of the light.

For a given emulsion, its response can be characterized by the so-called H & D curve (from Hurter & Driffield), such as the one shown in Fig. AI.1. It is a plot of *density* (D), such as measured by a microdensitometer, versus the logarithm of exposure (log E), where E is the amount of light energy per unit area. The actual shape of this curve depends in a complicated way on the nature of the emulsion and the developer, as well as the time and condition during development. The slope of the linear region of this curve is called gamma, γ.

For holography, it is more fruitful to plot on the abscissa, instead of density, the amplitude transmittance(29) T, which is the fraction of the light amplitude falling on the processed emulsion that gets transmitted. A typical curve is shown in Fig. AI.2 in relative units.

Referring back to Exercise I, consider that the emulsion is exposed to the reference beam alone. Since no interference takes place, the processed plate will show a uniform T. If, however, both the reference and the object beams are exposed together, interference will take place and a sinusoidal variation in T is recorded. We can call on an electrical analogy in radio and say that the reference beam – the carrier – has been modulated by the object beam – the signal. Carrying the analogy further, we can call the reference beam the "dc" bias because alone, it brings us to the middle of the linear region of the characteristic curve. Quite obviously, for any emulsion, the reference beam should always be more intense than the object beam; otherwise we would "over-modulate" into the nonlinear regions. Also, the exposure time is highly critical; and under- or overexposure again brings nonlinear response. For a given characteristic then, one can in principle determine the correct beam intensity ratio as well as the exposure time. However, in practice, this is more easily done experimentally.

Suppose we wish to make a sine grating. If we confine ourselves to Θ's less than, say, 10°, most commonly available black and white films (such as Kodak Plus-X) can be used. Since these films are very "fast", the best way to use them is to load them into a camera with a focal plane shutter and remove the lens. Use a light meter in the film position and check the intensities of the two beams individually by covering one beam at a time with a card, and making certain that one beam is at least one "stop" more intense than the other. Many different exposures can be made and the film is then developed according to the manufacturer's instruction. Once the optimum beam ratio and exposure time is determined, an experiment can be done to measure the ultimate resolution of a given film by increasing Θ until the grating fails.

At this writing, the most commonly used emulsion in high spatial frequency holography is the

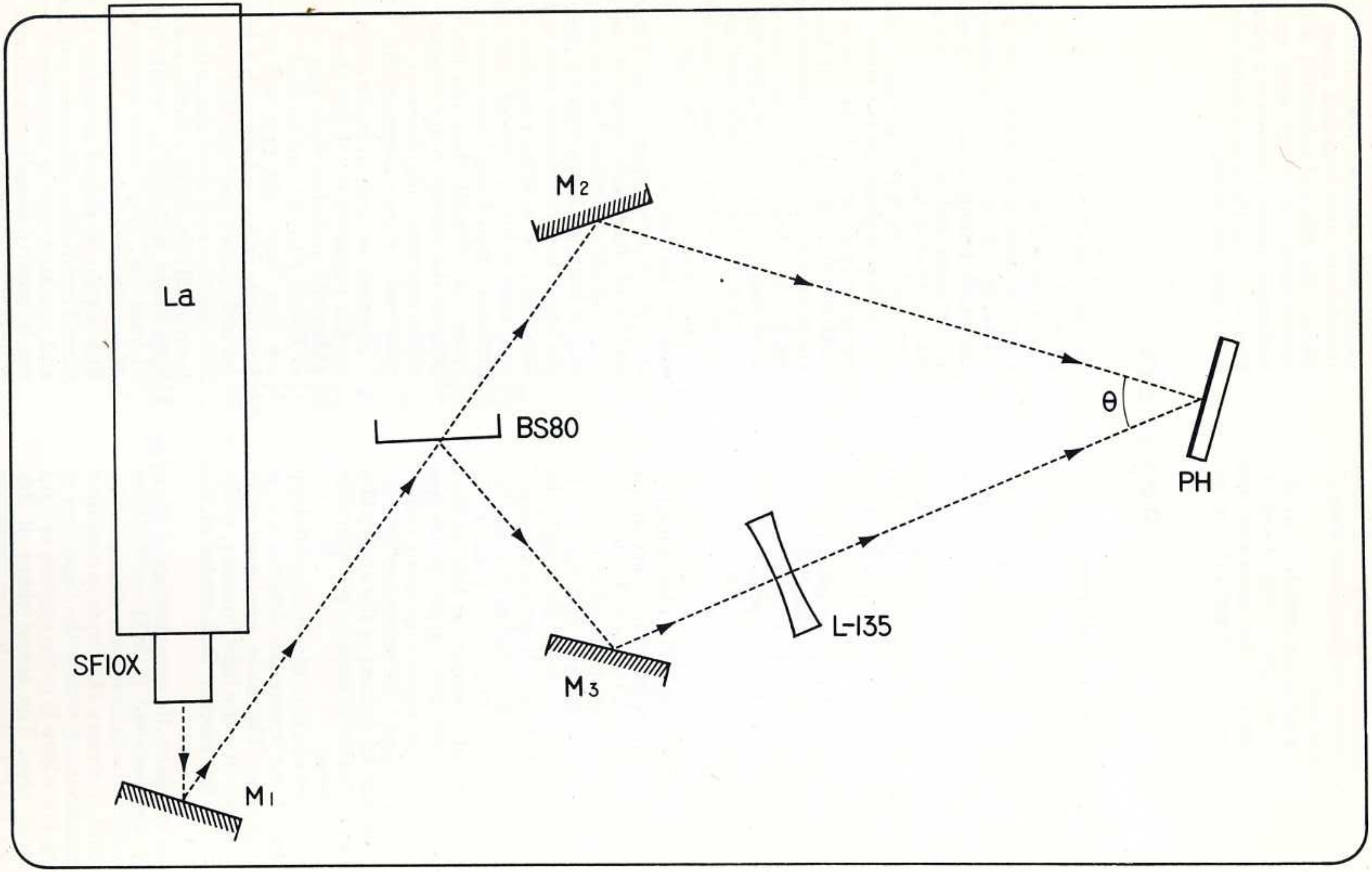

Figure AII·1

Kodak 649F film or plate. It has the capability of resolving several thousand lines per mm, which means, for light of wavelength 6328 Å, Θ can take on any value. Also, because its emulsion is about 16 microns thick, "volume" holograms which require the third dimension can be made with it.

For this particular emulsion, the optimum intensity ratio between the reference and the object beam is approximately 7.5 and the correct exposure is about 1100 erg/cm^2(29), equivalent to the photographic ASA rating of 0.003.

In practice, use the negative lenses (as shown in Fig. III.2) to diverge the beams so that when checked individually with a photographic light meter, the reference beam is about three "stops" brighter than light coming from the illuminated object. The measurement is, of course, made at the position of the plate or film. Even without a light meter, one can make a very good approximation by observing by eye, one beam at a time, after allowing each to reflect off a piece of white paper held in front of the plateholder. Make sure that the reference beam is about twice as bright as the object beam.

The error arriving from the beam ratio will affect only the amplitude of the signal during reconstruction (See Fig. AI.2), but an error in exposure can cause complete failure. To find the correct exposure, the "step-wedge" method should be used, and will be described later.

Light scattered from the scene is usually quite uniform, especially if the scene is composed of diffusing objects. However, the reference beam has a Gaussian profile, i.e., the beam intensity as a function of distance from the center falls off according to a Gaussian curve. The negative lens is introduced into the reference beam to spread it out so that when it intersects the photoplate, its intensity is reasonably uniform. After this is achieved and the beam ratio is established, the "step-wedge" technique is applied.

(**Caution:** After handling the plateholder, or anything on the vibration isolated table, wait a few seconds before making the exposure to allow the vibration to subside. If the photographic plate is handled, allow time for it to reach thermal equilibrium with its environment. Also, excessive acoustic noise should be avoided.)

After the exposure is made, process the 649F plate (or film) as follows:

1. Develop in D-19 for five minutes at room temperature
2. Soak in stop bath for thirty seconds
3. Fix in Kodak Rapid Fix with hardener for two minutes
4. Wash in running tap water for about ten minutes
5. (Optional) Soak in a solution of Photo-Flow for two minutes
6. Allow to dry vertically without wiping

If other brands of emulsions are used, follow the normal processing procedures recommended by their respective manufacturers.

A darkroom is usually required for handling fast photographic materials. However, if the film is already loaded into a camera body as noted before, the holographic setup can be used in a partially darkened room. If a slow emulsion, such as Kodak 649F is used, much room light can be tolerated. In fact, room light has been used to uniformly expose the emulsion near the center of the linear region of the characteristic curve, and simultaneously record the hologram. The general rule of thumb here is that the background light intensity should not exceed that of the laser, as received on the surface of the photoplate.

In general, if the room light is barely sufficient to make things visible after dark-adaptation, its presence need not be considered, so long as 649F is used.

The correct exposure time for a light level of 8 foot-candles is approximately one minute.

For testing purposes, it is economical and convenient to tape a 5 inch piece of 649F 35 mm film vertically on a 4″ x 5″ glass plate with the emulsion side facing the beams. To make the exposure test (after the beam ratio has been established), the dark side of the plateholder is pulled up ½ inch and a short exposure is made. Then the dark side is pulled up another ½ inch and the same exposure is made. This process is continued until the entire strip of film has been exposed. Upon development, obtained exposures will be varying from one to ten times the single exposures, and the best one can be chosen. The above process was previously referred to as "step-wedge" technique.

If the equipment is situated in a room that cannot be darkened, the following procedure is advised: attach one magnetic base on each corner of the bench frame; mount a ½ meter rod on each base; drape over the four rods with a large piece of soft and opaque cloth such as black velvet. This "room" is now sufficiently dark for handling slow emulsions.

The technique of bleaching the hologram(30, 31), changes it from an amplitude to a phase grating, thus enhancing the brightness of the reconstructed image(23). The bleaching solution is made by mixing 22.5 gm each of potassium bromide (KBr) and mercuric chloride ($HgCl_2$) in one liter of water. After the hologram is completely processed according to previous instruction, including the final washing, it is soaked in the bleaching solution until all the dark matter has disappeared. This usually takes less than one minute in a fresh bleach. The pinkish hologram is again washed in running tap water for about ten minutes and then allowed to dry at room temperature.

II. On The Use Of Other Lasers

In general, any laser emitting a sufficient amount of coherent light can be used with the Gaertner-Jeong holography system. The differences in the setups from the foregoing diagrams depend mainly on the dimensions of the laser.

If a sufficiently small laser is used, it can be mounted on a rod and magnetic base so that the beam level is at the same elevation with the rest of the optics. The beam deflector is then no longer required for Figs. I.1 and II.1. For Fig. I.2, II.2, III.1, III.2, and V.1, the beam deflector should be substituted by a mirror (page 6) and a magnetic base. Also, the spatial filter can be placed immediately after the laser, as shown on Fig. AII.1.

If the laser used is too large to be conveniently accommodated on the bench, it can be used from outside the system. For convenience, an extra beam deflector should be available to deflect the beam from the laser toward the bench. The rest of the setup is unchanged from the diagrams.

Vibration isolation for the laser is not critical, i.e., it can be simply placed on an out-of-the-way shelf. The phase relationship between the object and the reference beams is defined by the optical path difference between the beam splitter and the photoplate, but not before the beam enters the beam splitter.

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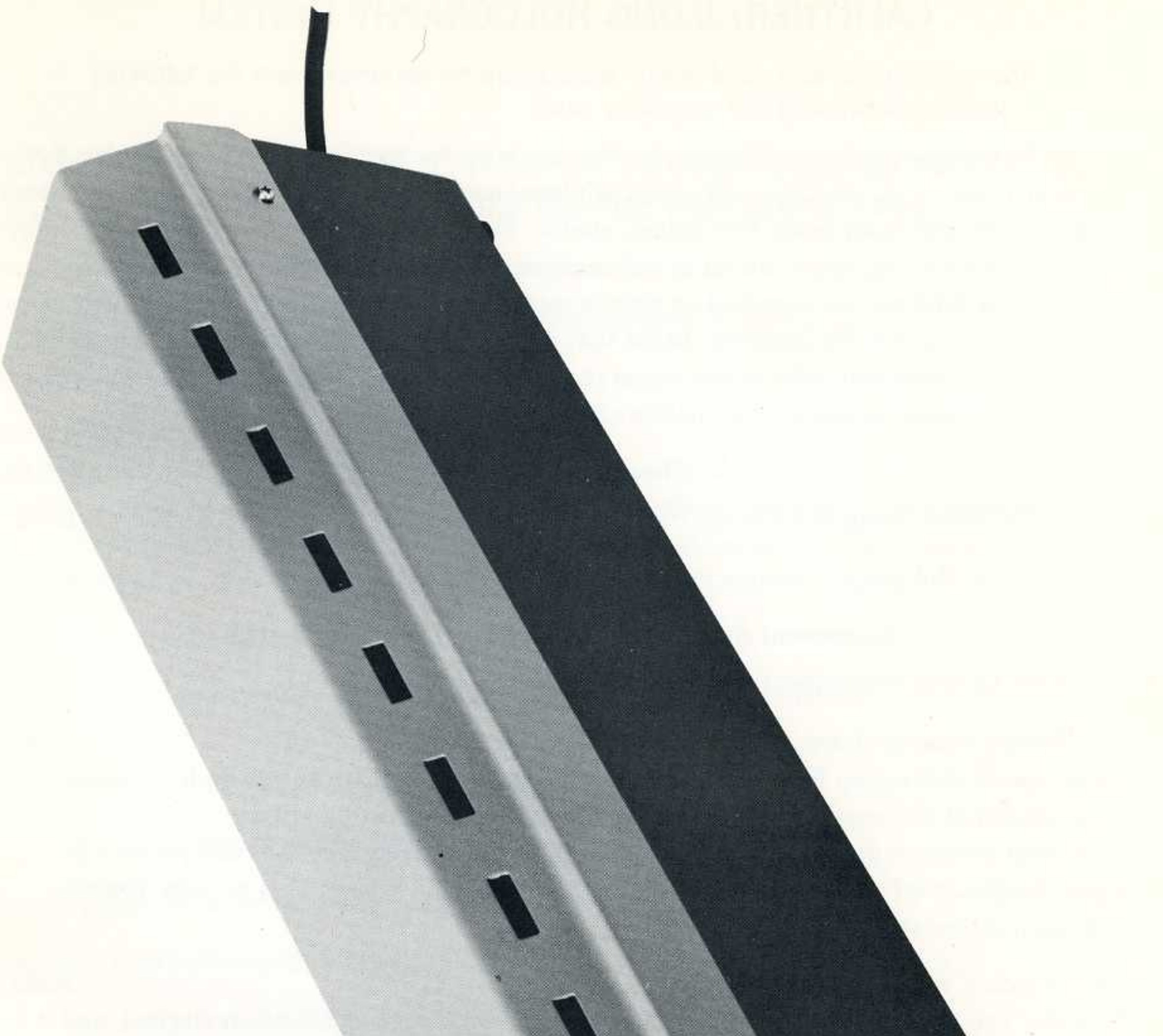


HELIUM-NEON GAS LASER AVAILABLE FROM GAERTNER FOR USE WITH GAERTNER-JEONG HOLOGRAPHY SYSTEM.

GAERTNER/JEONG HOLOGRAPHY SYSTEM

The experiments described in this manual can be performed with the following scientific instruments and accessory items.

The complete Gaertner-Jeong Holography System includes the Gaertner Rectangular Optical/Instrument Bench with air suspension and peripheral metal frame; two mirrors; beam splitter; two beam spreaders; specimen table; film holder; spatial filter; beam deflector and laser. The mirrors, lenses and beam splitter are mounted in yokes permitting tilt adjustment. All components except laser and beam deflector are mounted on rods in support tubes providing rotation and vertical positioning, and on controllable magnetic bases that can be mounted on the multi rails, across the rails, or on the metal edges and sides of the frame in almost any orientation. The support for one of the beam spreaders incorporates a cross motion slide.

Holography Systems	**Cat. No.**
Complete Gaertner-Jeong Holography System including Laser	R222
Gaertner-Jeong Holography System less Laser	R220
Component Assemblies of Complete Holography System	
Rectangular Optical/Instrument Bench with air suspension base	R210
Laser, Helium-Neon gas laser Single mode, diffraction limited power output 2mw at 6328 A. Brewster window plasma tube. External mirrors, factory pre-aligned, wavefront correcting output mirrow, Self-contained power supply operating at 115V, 60 cycles. Divergence 0.3 milli radians $\frac{1}{2}$ angle. Single on-off switch. Dimensions—22″ x $5\frac{3}{8}$″ x $4\frac{3}{8}$″. Weight $11\frac{1}{2}$ pounds. Plasma tube guaranteed one year.	R290
Beam Deflector. Attaches to R290 Laser. Includes two adjustable mirrors, 13 mm diameter rod threaded 3/8-16 on one end, and mounting bracket.	R258
The following units include yokes, rods, support tubes with 13 mm holes and magnetic bases:	
Mirror (2 required for Complete Holography System) includes R280H, R225A. . . .each	R255
Beam Splitter includes R280H, R260A	R260
Beam Spreader includes R280H, R265A	R265
Beam Spreader with cross slide, includes R280L, R285, R265B	R265X
The following items include rods, support tubes with 13 mm holes and magnetic bases:	
Spatial Filter includes R280H, R250A	R250
Specimen Table includes 280H, R270A	R270
Film Holder includes R280H, R275H	R275

Component Assemblies of Gaertner/Jeong Holography System Less Laser

Same as above except includes:
(3) R255 Mirrors and does not include R258 Beam Deflector.

FOLLOWING IS A COMPLETE LISTING OF INDIVIDUAL ITEMS MAKING UP THE VARIOUS ASSEMBLIES ON THE PRECEDING PAGE.

Components	Cat. No.
Rectangular Optical/Instrument Bench without air suspension base	R200
Spatial Filter includes R250F, S201-4 rod	R250A
Spatial Filter, only Unmounted. Incorporates 10X achromatic objective with provision for focusing, 25 micron pinhole with centering adjustment, and cable release shutter. Hole in bottom is tapped 3/8-16 to fit rods S201-3 and S201-4. Other objectives and pinholes can be easily interchanged.	R250F
Mirror includes yoke mounting, S201-4 rod	R255A
Beam Deflector, with mirrors and 13 mm rod tapped to fit R280M, without mounting bracket	R258A
Beam Splitter includes yoke mounting, S201-4 rod	R260A
Beam Spreader includes yoke mounting, S201-4 rod	R265A
Beam Spreader includes yoke mounting, S201-3 rod	R265B
Specimen Table includes S201-4 rod	R270A
Film Holder, only, includes S201-3 rod	R275H
Magnetic Base, 118 mm high support tube with 13 mm diameter hole	R280H
Magnetic Base, 86 mm high support tube with 13 mm diameter hole	R280L
Same as above but with cross slide R285	R280LX
Magnetic Base, only, with 3/8-16 tapper hole in top	R280M
Magnetic Base, 118 mm high support tube with 19 mm diameter hole	R281H
Magnetic Base, 86 mm high support tube with 19 mm diameter hole	R281L
Same as above but with cross slide R285	R281LX
Cross Slide, only	R285
Rod, 13 mm diameter x 76 mm long, threaded 3/8-16	S201-3
Rod, 13 mm diameter x 108 mm long, threaded 3/8-16	S201-4

OPTICAL BENCHES AND ACCESSORIES

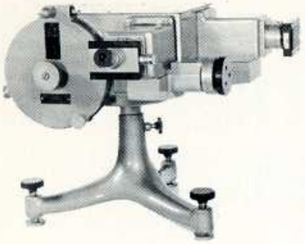
The rectangular optical/instrument bench featured as a component part of the Gaertner-Jeong Holography System is the latest in a complete line of benches offered by Gaertner. Other benches manufactured by Gaertner Scientific Corporation include the single rod, double rod and lathe bed types.

Users and prospective users of the rectangular optical/instrument bench will be pleased to know that most of the accessory items designed for use with the rod and lathe bed types are interchangeable and can be used on the rectangular bench.

You may obtain your copy of our complete optical bench catalog and price list by writing to Gaertner Scientific Corporation, Chicago, Illinois 60614. Ask for bulletin 156.

OPTICAL/INSTRUMENT BENCH

EXTENSOMETER



MONOCHROMATOR

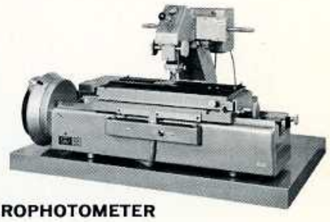
BULLETINS: *(FREE FOR THE ASKING)*

These bulletins contain technical information and specifications of each Gaertner instrument listed. Please request your choice of bulletins by stating the number preceding the listing.

181-65	Coordinate Comparator (M1225-37) range: 80MM x 100MM 360°
169-65	Coordinate Comparator (M1229) range: 100MM x 80MM
187-65	Coordinate Comparator (M1231) range: 50MM x 150MM
191-65	Coordinate Comparator (M1233) range: 255MM x 255MM
196-55	Coordinate Comparator (M1234) range: 150MM x 125MM
197-55	Coordinate Comparator (M1250) range: 50MM x 100MM
202-65	Coordinate Plate & Film Comparators (M2001P) range: 50MM x 100MM
192-65	Linear Comparator (M1177) range: 150MM
170-65	Linear Comparator (M1201-30B) range: 100MM
176-65	Linear Comparator (M1205C) range: 255MM
198-62	X-Ray Film Comparator
162-65	Cathetometers
162-65A	Convertible Cathetometer (M912)
194-65	Coordinate Cathetometers
140-65	Dilatation Interferometer
163-65	Michelson Interferometers
163-63B	Twyman-Green Interferometers
204-65	Vibration Interferometer
167-65	Collimators and Telescopes
207-63	Light Sources (Illuminators)
161-65	Measuring Miscroscopes for Laboratory and Shop
147-65	Toolmakers' Microscope
161-64A	Coordinate Measuring Microscope
176-65	Precision Linear Scales
164-66	Universal Laboratory Supports
166-65	Gates Concentrated-Arc Lab-Unit
160-65	Adjustable and Fixed Slits
154-63	Spectroscopes (Bunsen-Kirchhoff)
157-65	Divided-Circle Spectrometers and Accessories
206-65	Gaertner-Peck Spectrometer (Student)
203-65	Ellipsometers
184-55	Ring Spherometer
200-55	Spectroscopic Analysis Assembly
158-65	Wavelength Spectrometers and Monochromators
156-65	Optical Benches and Accessories
143-65	Photoelasticity Polariscopes
143-65A	Photoelasticity Polariscopes
159-59	Refractometer for Turbid Liquids
201-65	Viscometer

MICROCOMPARATOR

SPECTROSCOPE



MICROPHOTOMETER

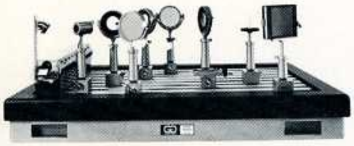
ELLIPSOMETER

REFRACTOMETER

CATHETOMETER

INTERFEROMETER

TOOLMAKERS' MICROSCOPE



RECTANGULAR OPTICAL
INSTRUMENT BENCH

DIVIDED-CIRCLE SPECTROMETER

COORDINATE CATHETOMETER

He-Ne LASER

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