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ABSTRACT

This is one of several study guides on contemporary problems produced by the American Association for the Advancement of Science with support of the National Science Foundation. The primary purpose of this guide is to provide a student with sufficient practical and technical information to begin independently practicing holography, with occasional help from a teacher. Included are the following chapters: (1) Introduction; (2) Holographic Characteristics; (3) Geometric Models; (4) The Fourier Description; (5) Material Requirements; (6) Preliminary Experiments; (7) One-beam Holograms; (8) General Multiple Beam Hologram Formation; (9) Basic Projects; and (10) Bibliography. The Appendices include sections on: (1) Chemical Processing Procedures; (2) Photographic Materials for Holography; and (3) The Integration of Motion Pictures into Holograms. Drawings and figures are used to help illustrate the guide. (RH)

TEST EDITION

A STUDY GUIDE ON HOLOGRAPHY

(Draft)

by

Tung H. Jeong

|A|A|A|S| Study Guides on Contemporary Problems

A part of the
NSF Chautauqua-Type Short Courses for College Teachers Program

A STUDY GUIDE

ON

HOLOGRAPHY

(Draft)

by

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Printed in the United States of America

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AAAS STUDY GUIDES ON CONTEMPORARY PROBLEMS

Since 1970 the American Association for the Advancement of Science has conducted the NSF Chautauqua-Type Short Courses for College Teachers Program with the support of the Education Directorate of the National Science Foundation. More than 9,000 college teachers of undergraduate students have participated in the courses which have dealt with either broad interdisciplinary problems of science or the applications of science and mathematics to college teaching. All of the courses are designed to make available the most current information.

Much work goes into the preparation of NSF Chautauqua-Type Short Courses, yet there are only limited numbers of places in the classes for college teacher participants. In order to make some of the instructional materials more widely available, the AAAS introduced the Study Guides experiment in 1974-75. Course Directors prepared test editions of Study Guides for review by participants in the classes in 1974-75. These seven Study Guides are now being edited for publication, and should be available from AAAS by late 1975.

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PREFACE FROM AAAS

TO STUDY GUIDE REVIEWERS:

The test editions of the set of six Study Guides were prepared on relatively short notice by the course directors during the summer of 1975. To provide as much information as possible to the authors for use in revising this study guide for publication, we ask you as a participant in the NSF Chautauqua-Type Short Course to test these materials and provide your reactions. Also we would appreciate receiving reactions of your colleagues and students if that is possible. Your efforts will contribute significantly to the quality of the revised Study Guide.

If this Study Guide has been successfully prepared, upon completing it, you will: (i) have an overall comprehension of the scope of the problem, (ii) understand the relationships between aspects of the problem and their implications for human welfare, and (iii) possess a reliable guide for studying one or more aspects of the problem in greater depth. We ask you to evaluate the study guide on the basis of how well each of these objectives is achieved. Of less importance but most welcome are your specific editorial suggestions, including punctuation, syntax, vocabulary, accuracy of references, effectiveness of illustrations, usefulness and organization of tabular materials, and other aspects of the draft that are related to its function. Three copies of an evaluation form follow this page and additional copies may be reproduced if needed. Each evaluator should return a completed form to: NSF Chautauqua-Type Short Course Program, AAAS, 1776 Massachusetts Avenue, N.W., Washington, D.C. 20036. Please type or print legibly. Feel free to include any additional comments you care to make. This evaluation is in addition to any evaluative requests made by the study guide authors; however, we do encourage you to cooperate with all requests from authors. Your efforts in evaluating this Study Guide are a worthwhile contribution to the improvement of undergraduate education and we express our appreciation to you.

We hereby gratefully acknowledge the services of Joan G. Creager, Consulting Editor, and Orin McCarley, Production Manager for this series.

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Acting Director of Education
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AAAS EVALUATION FORM

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CHAPTER I

Introduction

The basic ideas of holography were originated by Professor Dennis Gabor in 1947 and published in 1948. With the advent of the laser and an improved process by Leith and Upatnieks, it caught the excitement and imagination of the scientific community and has since become an active field of applied research around the world.

More recently the introduction of motion and the elimination of stringent conditions for illumination have made it possible for artists without scientific background to adopt holography as a new and exciting medium of graphic communication. Thus, a new era of collaboration between scientists and artists has begun.

The primary purpose of this study guide is to provide a student with sufficient practical and technical information to begin independently practicing holography, with occasional help from a teacher.

In a way, this is more of a laboratory manual than a "study guide". The chief justification lies in the nature of the subject matter and the author's philosophy in science teaching. <u>The student should "do it" first</u>. The understanding and the formalism will come naturally once his interest and curiosity are aroused.

The content has been used by the author during the last three years in his Chautauqua Short Courses around the country, covering all the centers. In addition, it has also been used in a series of Hologram Workshops offered by Lake Forest College every June since 1971. Thus the content has been tested on a variety of students from thirteen-year old junior high school students to physics professors. Within this spectrum, we have had artists, entrepreneurs, medical doctors, psychiatrists, theatre designers, engineers, museum directors, architects, and unaffiliated itinerants. Hopefully, with the feedback of the initial users of this guide, we can improve the content, the format, and especially add a section of homework problems to it.

In writing this guide, I am compelled to justify the teaching of holography in an institution of formal education. First of all, holography is not merely a craft - it combines meticulous laboratory techniques with extremely elegant formal theory. Indeed, a single hologram contains all the major theories of physical and geometric optics. With laboratory practice, the student will learn the importance of attention to pertinent details and the painstaking care required to achieve experimental results. In Chapters III and IV he will learn the interplay of deduction and induction in scientific pursuit. Finally, we shall put holography in perspective and show that it is a fundamental exposition on the wave behavior of electromagnetic radiation.

Thus, while studying holography, one can leap into the study of quantum physics involving the laser, the general consideration of information theory involving the topic of entropy, as well as the symmetry between the spatial and the temporal domains of communication theory. Indeed, this is an open-ended subject that can be pursued at any level.

Although this guide is written in the usual format, i.e., beginning with introduction and some theoretical considerations and ending with laboratory exercises and a discussion of applications, it can be used in an almost random order. For example, the beginning student can start with Chapters VI, VII, and VIII and make holograms during his first laboratory periods. These chapters are self-contained and can be followed even without any essential understanding of holography. Outside the laboratory, he can read the preceding chapters to understand what he actually has accomplished.

I feel that this is a pedogogically sound procedure in that it follows the natural learning process of all of us, that is, we learn as we go. More specifically, I have found that by allowing a student to succeed in making a white light reflection hologram during his first exercise, he is encouraged to learn all the basic physics necessary to explain it to his peers as he exhibits it, and this alone requires that he learn at least three Nobel Prize-winning ideas in physics.

In other words, this procedure allows a parallel teaching of theory and practice. Since the subject can be pursued at many levels, both liberal arts and science students can participate simultaneously, making the subject of holography highly viable as a mini-course in a university curriculum, or as a topic of independent study for a student.

From the point of view of economics, the subject of holography offers advantage over many other experimental topics. A complete program in holography, including the laser as well as expendable materials, such as chemicals and film, can be started for less than $250. The full range of this homemade and commercially produced hard- and software will be discussed in Chapter V.

Chapter II describes what holograms are. It enumerates the characteristics that can be physically demonstrated in front of an audience with a set of standard holograms that can be either purchased or made. From past experience, I find that this is the most suitable way to begin a course or even a one-hour lecture on holography. It arouses curiosity and motivates the student to pursue the subject further.

Chapter [illegible] describes a geometric model which, with minimum mathematics, allows the general student to attain an intuitive understanding of holography. A more formal description is offered in Chapter VI. Here, a discussion of the interplay between practice and formal ideas is offered, hopefully to review to the student some degree of elegance involved in scientific pursuit.

Chapters VI, VII, VIII, and IX are structured. It is advisable to follow them in order as presented. Chapter VI can also be used as lecture demonstrations using the Michelson interferometer both as a historical experiment and a practical tool for checking vibration.

On the matter of bibliography, I decided to break tradition and do it in a novel way. Instead of inundating the student by showering him with numerous footnotes and references, most of which he cannot understand, I have decided to have an independent chapter on references at the end of this guide. Thus, Chapter X is not merely a list of references, but contains a general discussion of various types of references and how a student should use them. Included are a sampling of general physics textbooks which should be consulted by a student whenever he encounters a technical terminology that he cannot comprehend. Any single text on the subject of holography will contain hundreds of other references. For this reason only a few pertinent original articles are included. Each article can induce an avalanche in other articles. For practical purposes a list of vendors for both hard- and software are listed. Here I must confess my bias in my choices. Essentially, it is impossible to list all competing manufacturers. What is listed represents my own personal choice. Since new products are being brought to the market periodically, the student is encouraged to do some research in this area and make some independent choices.

CHAPTER II.

Holographic Characteristics

What is a hologram?

We shall begin by enumerating general characteristics of most holograms, follow by a discussion of specialized types which have their own particular interesting applications. Chapters III and IV will explain most of the facts listed here.

1. The most striking feature of any hologram is the three-dimensional image that it forms. An observer looks through a hologram as if it were a window. A three-dimensional image of an object can be observed to be on either side or even straddling this window. As the viewer moves his head up and down and side to side, he can look around the object. In fact, what is observed is not a psychological effect but can be confirmed by scientific instruments, such as cameras or video recorders. This means that the light arriving from the hologram into the viewer's eyes is physically the same as light emitted from the original object.

2. If a hologram is broken into small pieces, (or, to be less wasteful, if the hologram is covered by a piece of opaque paper with a small hole in it) the entire image can be seen through any small piece. Depending on the location of the piece viewed, the perspective is changed. This resembles precisely the act of looking through a hole in a covered window. Depending on the location of that hole, the outside scene is perceived in its entirety, but from a different perspective.

3. Holograms offer both real and virtual images. An image is said to be real if it can be projected and focused onto a screen. Otherwise it is called a virtual image. In general, the definitions parallel to those used for classical optics concerning lenses and mirrors.

4. Holograms formed on thin emulsion exhibit the phenomenon of dispersion, that is, when the hologram is viewed with a white spotlight, such as from a slide projector, the image is observed as a continuous smear from blue to red. If it is illuminated from a point source of low pressure mercury light, discrete images in different colors can be observed.

5. Holograms can be made in shapes other than flat sheets. For example, a cylindrical hologram can be made with a single exposure, so that after processing, the viewer can walk around and observe the image from all angles. In general, any shape that can be formed by holographic film can be used to record holograms. Emulsions can even be coded inside bottles so that the contents can be holographed and later observed as virtual images.

6. A focused image hologram is one which can be illuminated by a point source of white light with the image appearing in black and white and in three dimensions at the film plane.

7. A "rainbow hologram" can also be viewed with a point source of white light. Depending on the angle between the illuminating light and the hologram, the image can be observed at any desired color one wishes. If this type of hologram is illuminated with a long, filamental white light, the image appears black and white.

8. All the previously mentioned holograms are usually called transmission holograms. They are always viewed by having the illumination behind the hologram on the side opposite from the viewer. The light transmits through the film to form the image that the viewer sees. On the other hand, a reflection hologram is a type in which the illuminating source is on the same side of the hologram as the viewer. Light is reflected off the hologram to form the image observed. This type of hologram can always be illuminated by a point source of white light and the image will appear in color. Using multiple-color lasers, holograms

of this type can give multi-color three-dimensional images.

9. The integram integrates various graphical techniques to allow the display of three-dimensional images of live objects in motion as well as outdoor scenes. The viewer standing around a transparent cylindrical drum sees people, microbes, or computer-generated three-dimensional images inside, in continuous motion. Since it is recorded from ordinary motion pictures originally in two dimensions, any images that can ordinarily be captured by the motion picture camera can be converted into an integraph. The largest object ever recorded this way is the earth with its cloud formation. The original data was gathered from weather satelites in two dimensions and then integrated into a hologram. In the present format, the integram requires monochromatic illumination. However, this constraint is eliminated if and when thick, phase-sensitive recording medium becomes available. It will then be possible to present the image in natural colors.

10. A multiplex hologram uses the combined techniques of the integram and the rainbow hologram. Its most important advantage is that it can be illuminated with a tungsten filament light bulb. However, depending on the angle the observer makes with the film plane, the image changes color from red to blue without any control and it cannot be seen at close range. At a distance, the three-dimensional image is extremely striking.

11. The image of the hologram can reveal more information than by the mere observation of the original object. For example, a specimen can be recorded so that black lines appear in the space surrounding its image. The shape and location of these black lines reveals the microscopic shifts on the surface of the object. This technique is called

holographic interferometry or, for short, <u>holometry</u>. A typical technique used to produce such a hologram is to first make an exposure, then allow the object to be changed by applying a force on it, (if it is a plant, allow it to grow for a short period of time) and then a second exposure is made. In the image of the processed hologram, one sees a comparison between the two states which reveals all the microscopic differences through these black fringes. Using this technique, vibration patterns on musical instruments, stress patterns as applied to structural parts, and growth patterns on live plants have been observed.

12. By using a two-frequency laser, contour lines can be mapped onto the surface of the image of an object. By observing the image of the hologram, quantitative information concerning the dimension along the line of sight is quantitatively observable.

13. Motion pictures, as we see them now, can be transferred into a holographic cassette which then can be played back through an ordinary television set. The major advantage here is that the recording medium is cheap plastic without coating. The interesting part of this hologram is that the film can be continuously moved, but the image remains stationary until the hologram of the next movie frame is in position. This characteristic is typical of a Fraunhoffer hologram. This allows the cassette to be played in a continuous manner, much like a magnetic tape and unlike the jerking motion of a motion picture projector.

14. If a lens or mirror or some other optical component is part of a scene inside a hologram, it retains its optical characteristic when the recorded image is viewed. For example, an object placed behind a lens will be seen to be magnified or minified. Such a hologram, when observed with a real lens can form a compound optical instrument, such as a microscope or a telescope, allowing the viewer to change focal distance of the system at will.

15. Images of non-existent objects can be recorded holographically through the assistance of a computer. Basically, the mathematics of holography is well-known and the pattern actually recorded on the photographic film during the formation can be calculated and plotted out by a computer. This pattern can be photographically reduced and viewed as a hologram. In a more straight-forward case, computers can initially generate two-dimensional sequential images of an event or a TV screen. These images are then transferred into a motion picture format and then converted into a integram or multiplex hologram. Furthermore, computer holograms can be used to compensate or correct optical defects of existing instruments.

The list of characteristics above by no means exhausts all the interesting aspects of holography. They were specifically enumerated to arouse the curiosity and interest on the part of the student. It challenges them to learn to understand each and every item and perhaps even to demonstrate them in the laboratory.

CHAPTER III

GEOMETRIC MODEL

To make holography accessible to the artist as well as to the technician, we here develop a geometric model to interpret various physical characteristics of holograms listed in a previous chapter. It is possible to understand much of holography without a highly mathematical background. However, to do quantitative work, rigorous mathematics is absolutely necessary.

TWO-SOURCE INTERFERENCE

Basic to this model is the understanding of how two sources of continuous waves, emitting at the same constant frequency, interfere in space. A popular demonstration of this is the ripple tank. Such patterns can be simulated by the superposition of two identical sets of concentric circles, where the radial difference between successive circles is λ, one wavelength (Figure 1). Assuming that the white areas represent constructive interference, and the dark areas represent destructive interference, tracing either set results in a family of hyperbolas. Figure 2 represents a set of constructive interference patterns. Along the zeroth order, all intersecting circles have a constant radial difference of 0; and along the nth order, the difference is $n\lambda$. In between the orders of maxima are hyperbolas representing the minima (not shown in Figure 2), where the wave amplitude is always zero inspite of the fact that waves from two sources of disturbances are continuously passing through.

If the two sources were operating in three-dimensional space, as would be the case for acoustic sources, the interference pattern would be represented by the figure of revolution of Figures 1 and 2 with the line connecting the two sources as the axis, i.e. a family of hyperbolas.

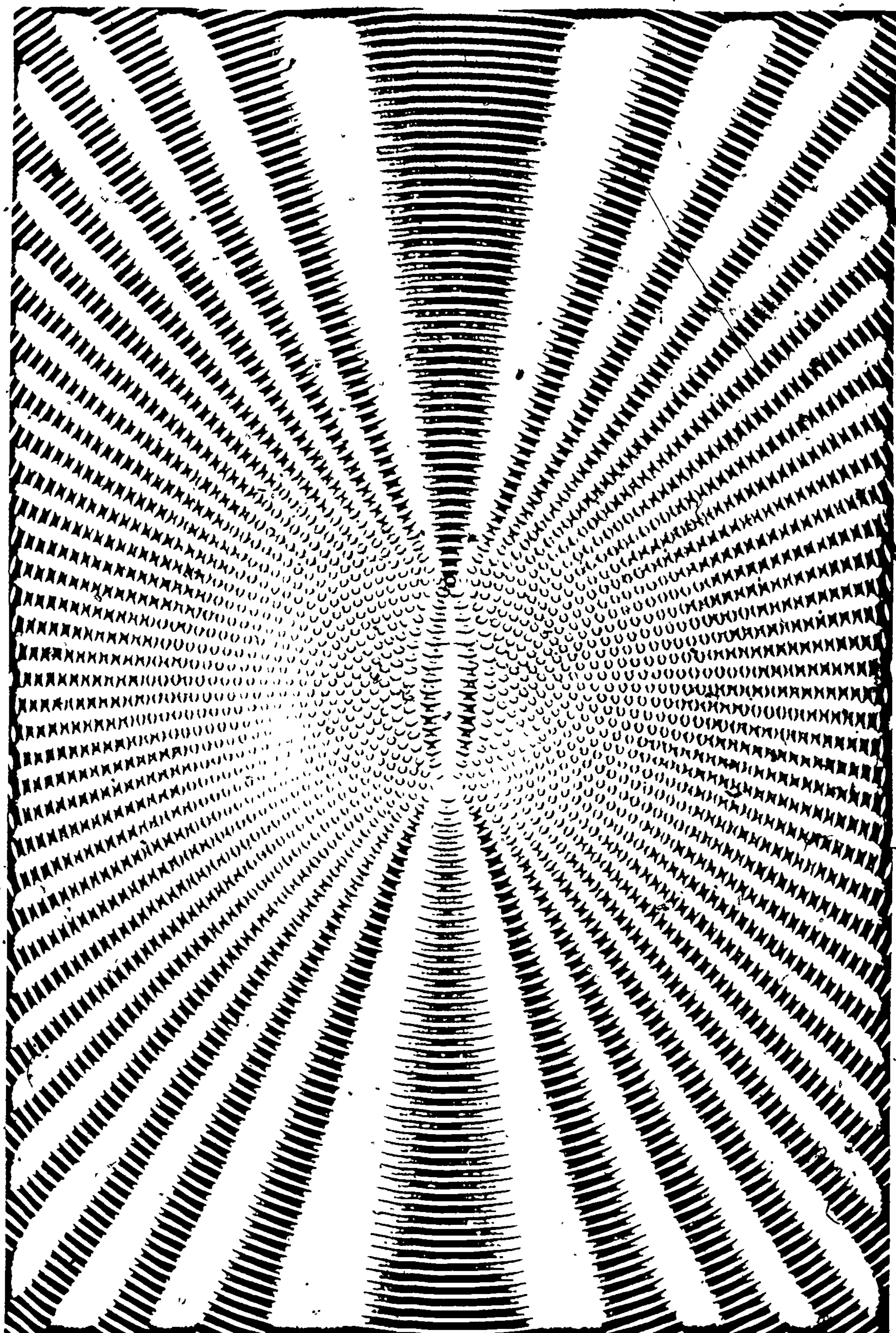


Fig. 1

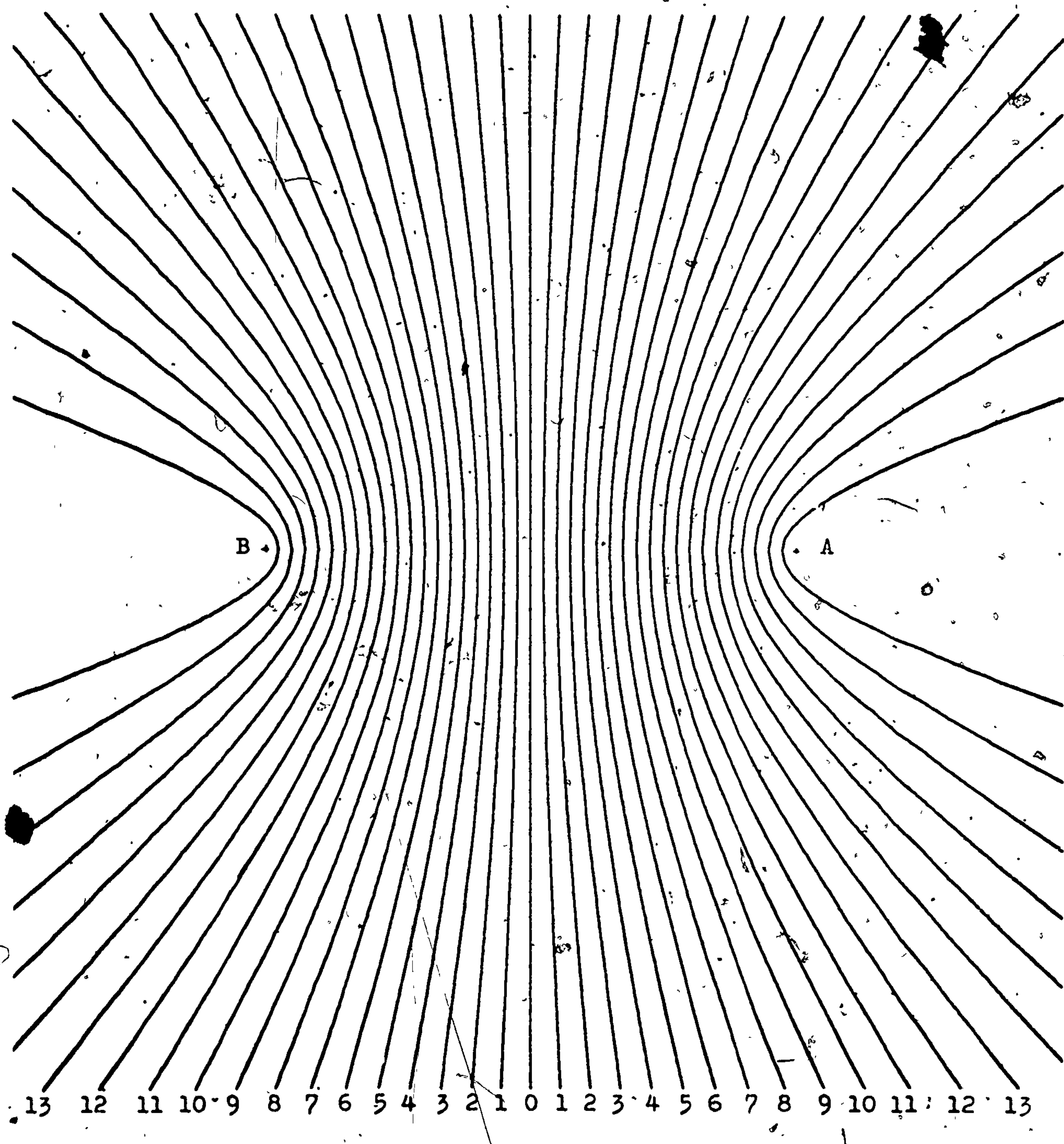


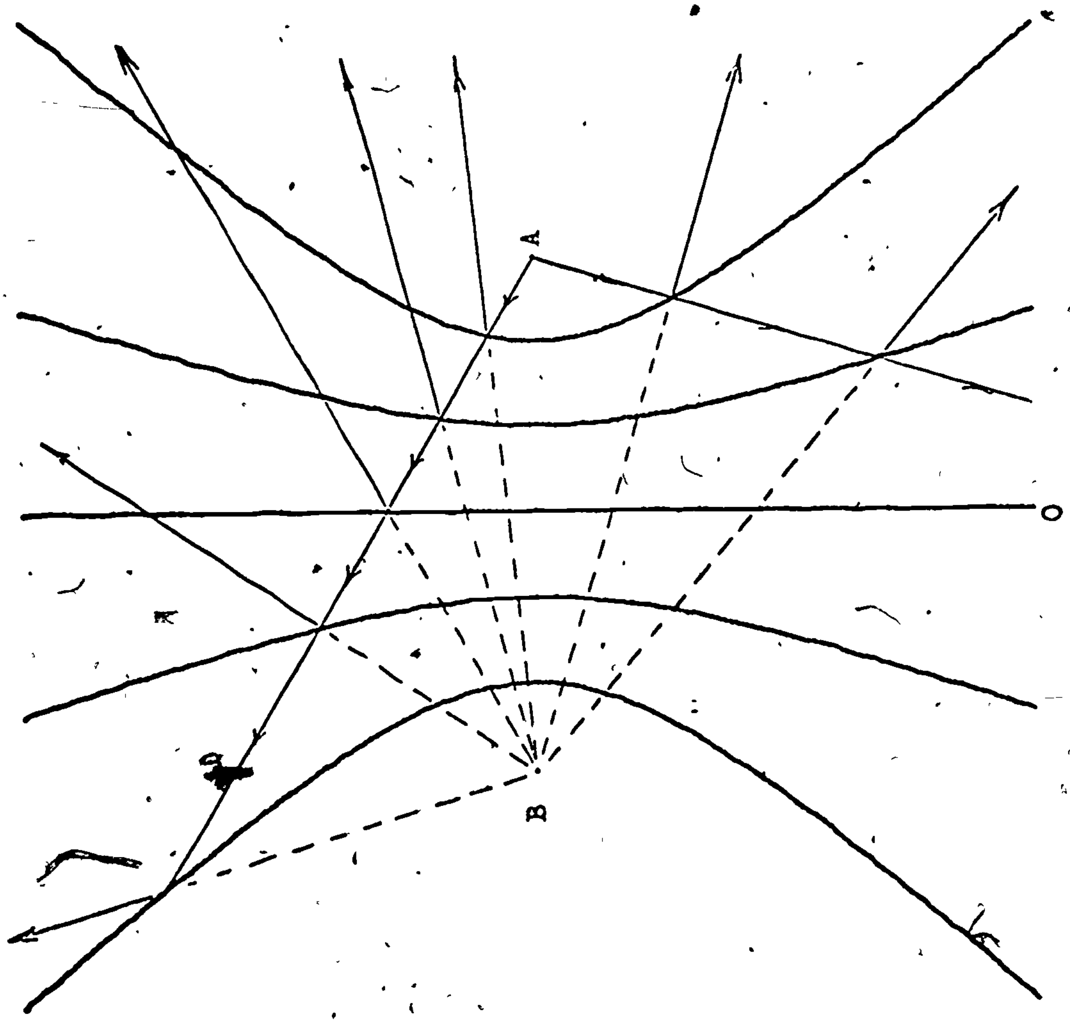
Fig. 2

If the two sets of concentric circles on Figure 1 were made on separate transparencies, they could be moved relative to one another to observe how the families of hyperbolas are changed relative to the positions of the two sources. This demonstrates the interference patterns generated by the Michelson interferometer and Young's double slit interference patterns.

THE MODEL

We would like to state some interesting, if not more well known, characteristics of hyperboloids as represented by Figure 3. Take the zeroth order, which perpendicularly bisects the line joining the two sources. If we imagine that this plane is a mirror, any ray of light arriving from source A would be reflected in such a direction as if it comes from source B. We can say that B is the virtual image of A. Now take an arbitrary order other than zero. Let us imagine that this hyperboloid is coated for reflection, i.e. a hyperbolic mirror. Any ray of light arriving from source A, once again, is reflected in such a direction as if it comes from source B. In both cases, a reciprocal statement can be made, i.e. that a light ray arriving from source B will be reflected by <u>any</u> portion of <u>any</u> hyperbolic surface in such a direction as if it were generated by source A. A more mathematical statement is that the tangent on any point of a hyperbola besects the angle formed by the two radii through that point.

A statement of our model can be presented as follows: Assume all hyperboloidal surfaces that represent the interference maxima due to two interference sources to be <u>partially</u> reflecting surfaces. When a hologram is made, the volume throughout the hologram contains a linear superposition of a multitude of hyperboloidal sets of partial mirrors, each set being created by the interference between the reference beam and light from a point on the object. When the hologram is viewed, each set reflects light from the reference beam and forms an image of an object point.



Fig, 3

APPLICATIONS OF THE MODEL

The Virtual Imagine - Figure 4 shows the optical case of a two-beam interference in three-dimensional space. Assume that the two sources are emitting at the same constant frequency and that we place a recording medium such as silver halide photographic emulsion at a position as shown. Since the typical thickness of these emulsions are in the vicinity of 10 λ, the interference pattern recorded inside the emulsion represents sections of hyperboloidal surfaces of many different orders. Imagine that after processing, these surfaces become partially reflecting mirrors (as well as partially transmitting and absorbing). By illuminating the processed film with source A only at the original relative positions (Fig. 5), some of the light is transmitted directly through these partial mirrors, some is absorbed, but the rest is reflected in such a direction as if they all come from source B. Therefore, if an observer looks in the direction of source B through the processed film-hologram, he sees a virtual image of B.

We can arbitrarily call the light from source A a reference beam and from source B an object beam. If more than one point source is located in the vicinity of B, each source will form a unique hyperboloid set with source A and the film will record all of them. Upon illuminating the processed hologram with source A only, each set will reflect light in such a way as to recreate the virtual image of all its object point.

If we now replace object B with a three-dimensional scene illuminated by light having the same constant frequency as the reference beam, each point on the surface of this object creates a unique hyperboloid set with A inside the emulsion. Thus, we have a hologram of a three-dimensional object (Figure 6).

The Real Image - Take the hologram from Figure 5 and illuminate it in a backward direction by focusing a beam of light back toward A (Fig. 7).

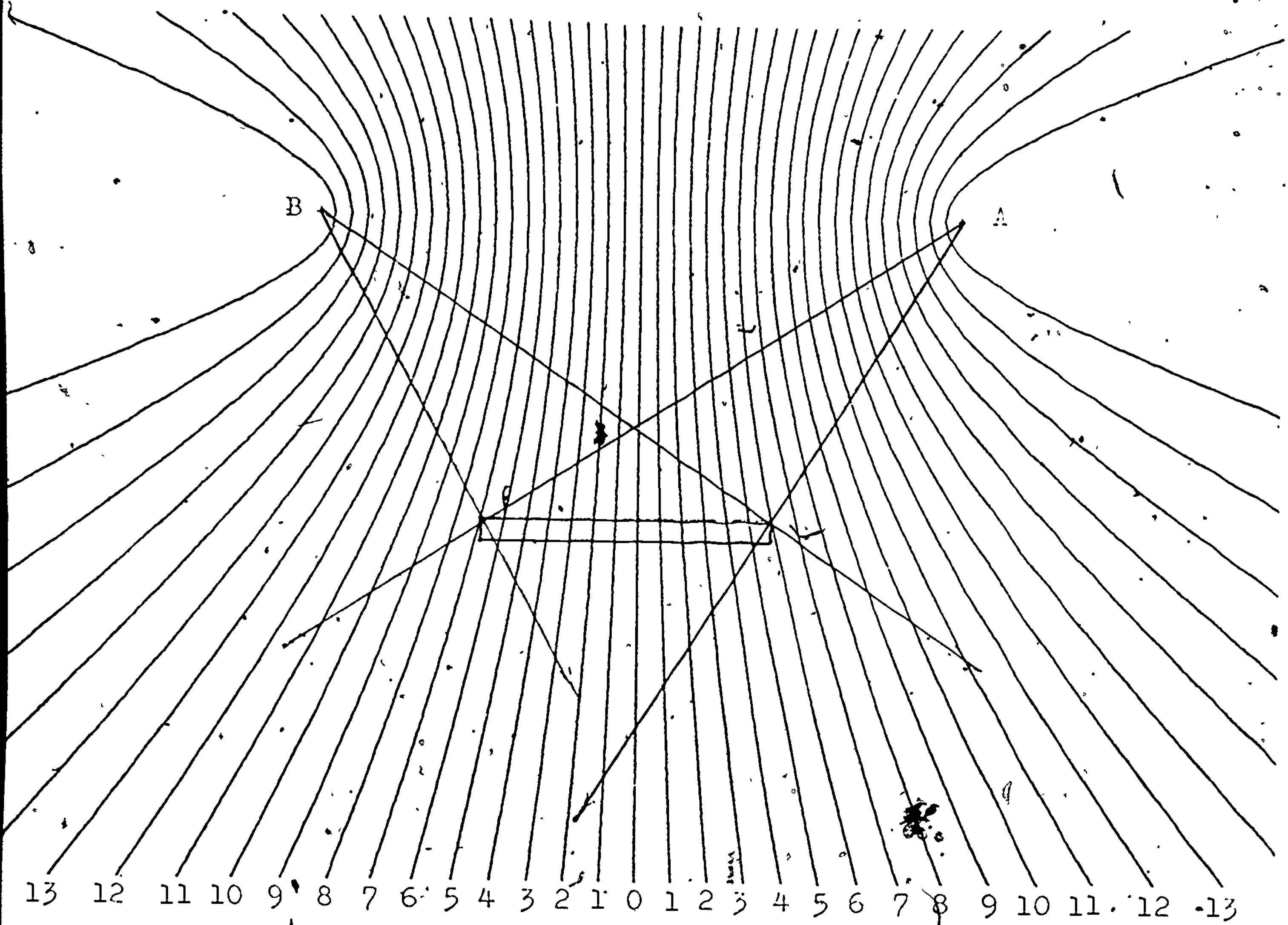
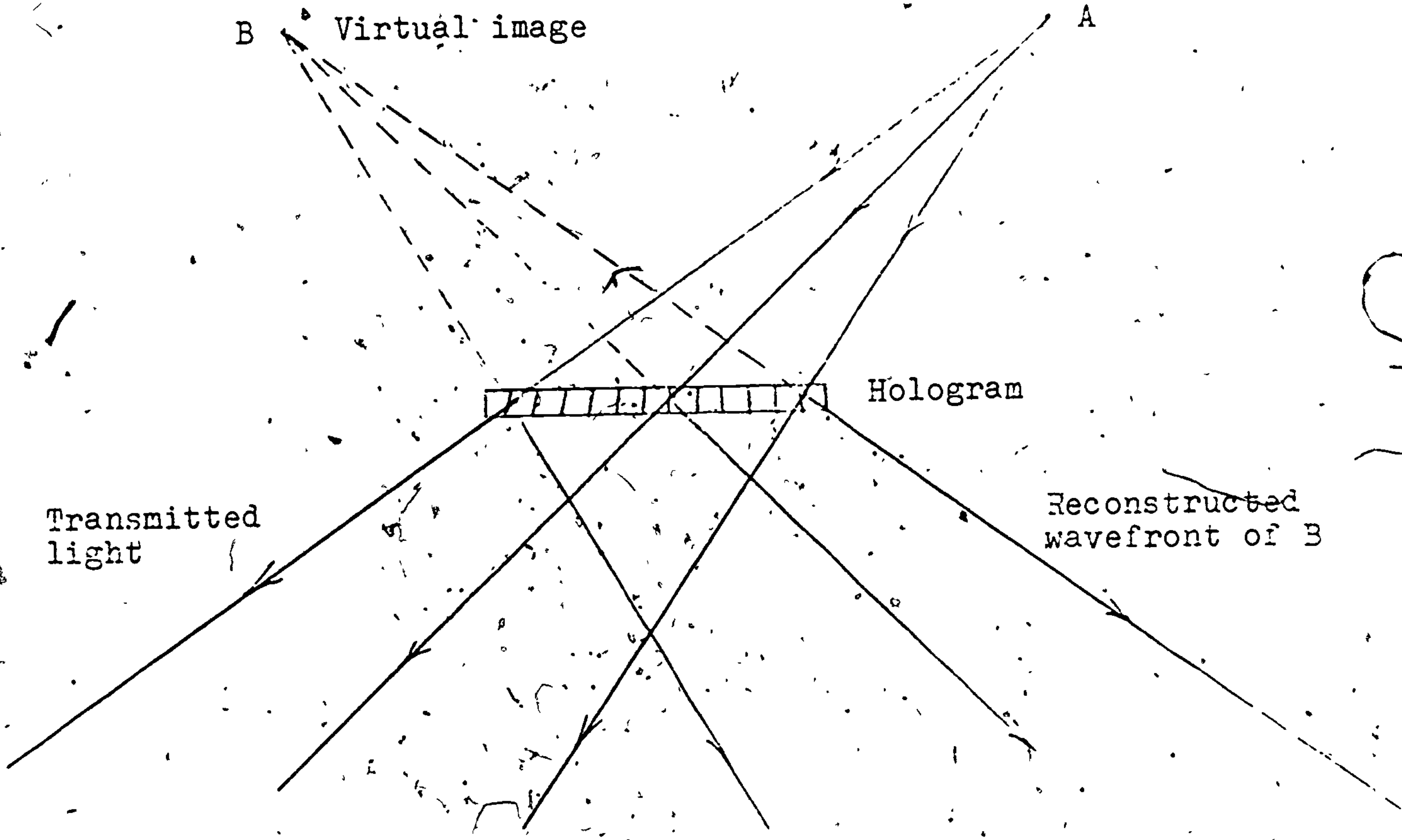
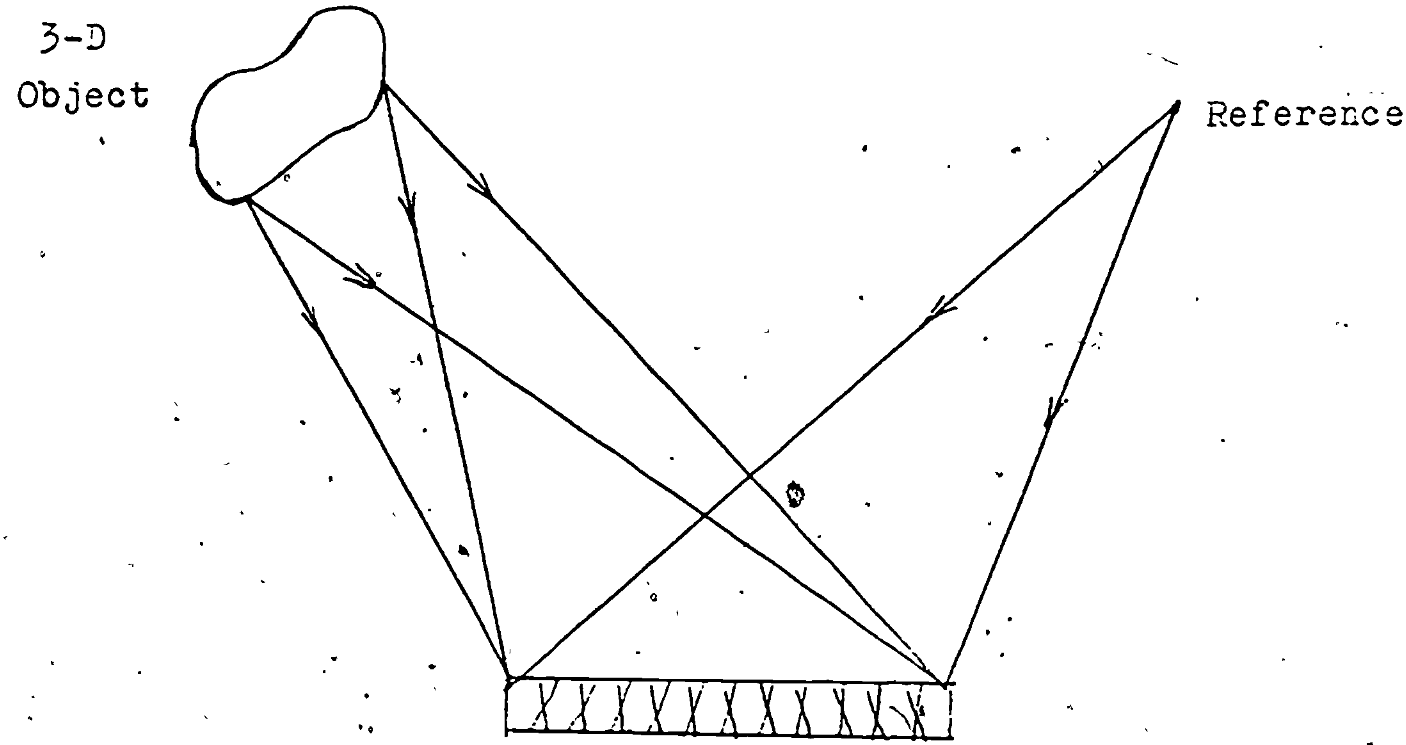
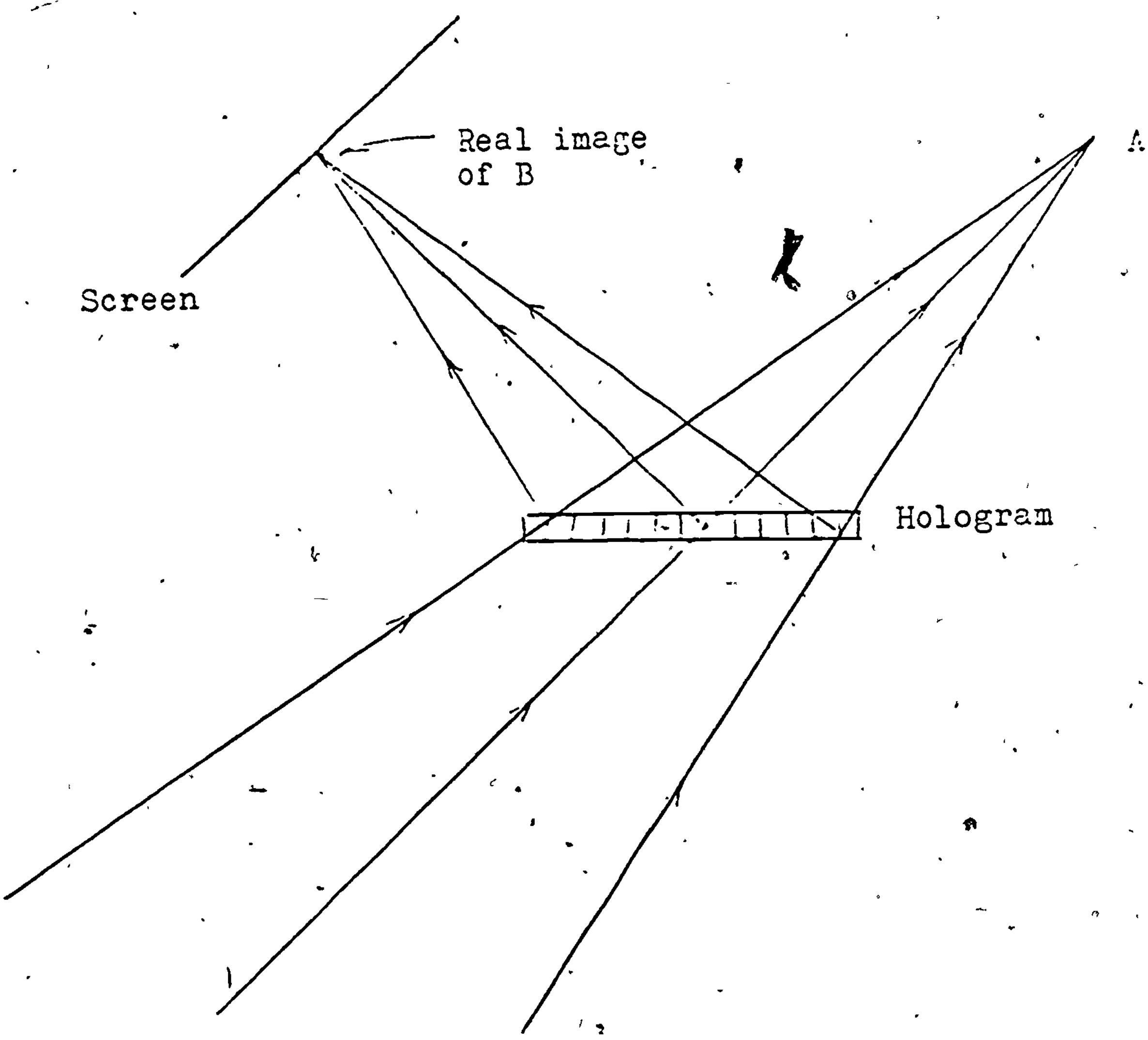


Fig. 4


B
Virtual image
A
Hologram
Transmitted light
Reconstructed wavefront of B

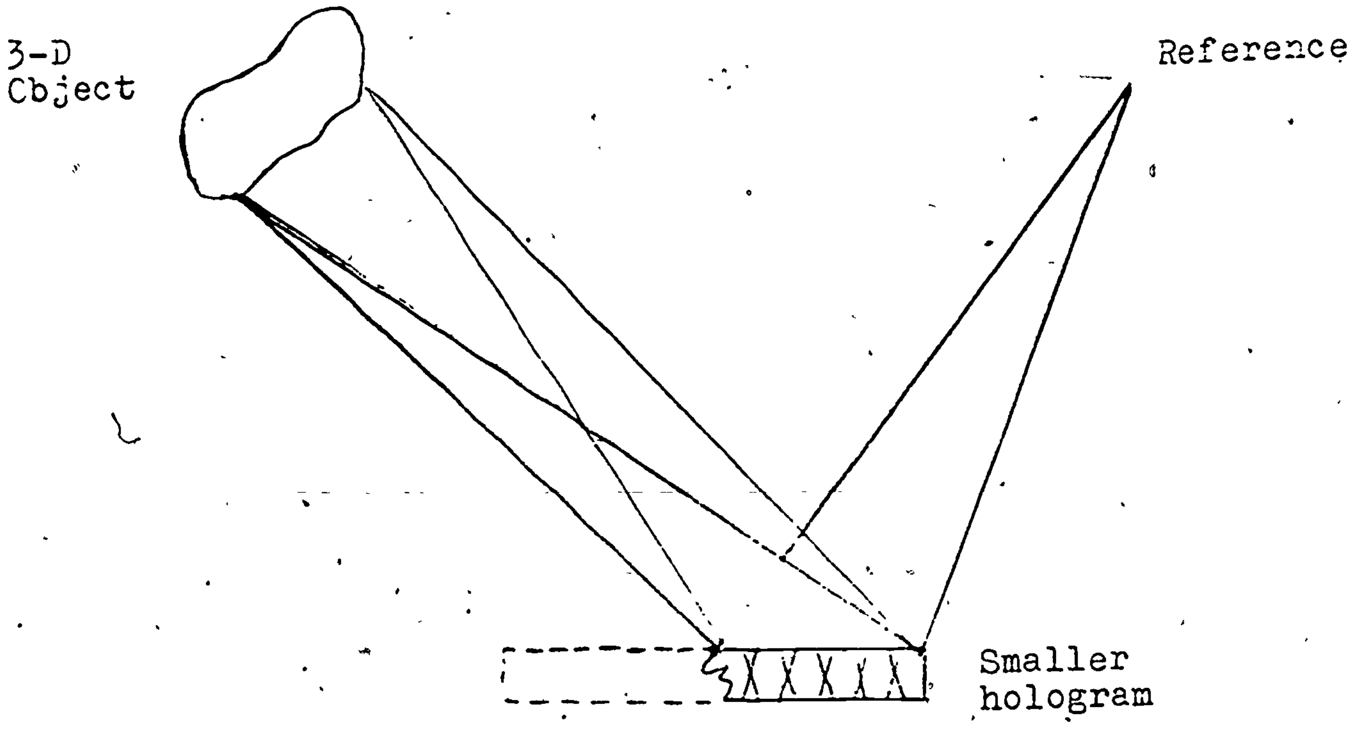

3-D
Object
Reference

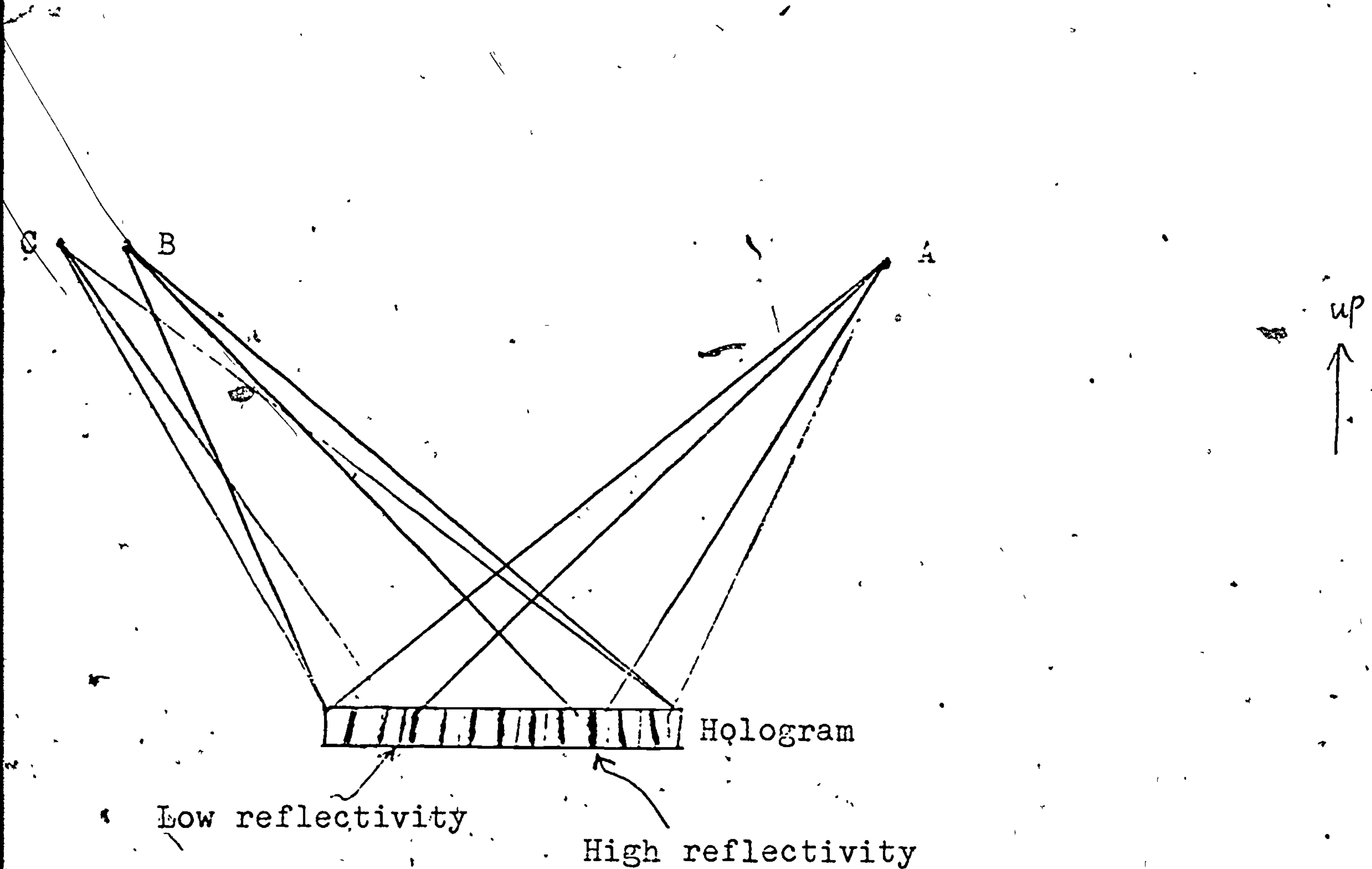

Real image of B
A
Screen
Hologram

The reflected light from our hyperboloidal mirrors will focus at B so that if a projection screen were present, there we would have a real image of B. This can be done also with the hologram formed in Figure 6. The real image in this case will appear on the screen as a two-dimensional image of our original scene. Depending on the location of the screen, different parts of this scene will come into focus.

Redundancy - It is well known that if a hologram is broken into pieces, each piece will give a complete perspective of the original scene. This can be understood from Figure 8. Imagine that the film were half or a small fraction of its original size as shown in Figure 6. Since every elementary volume in the hologram was formed with light from a complete perspective of the scene, each of these elementary volumes will produce a complete perspective. In other words, the size of the film used to form a hologram is independent of the size of the scene. In fact, for the purpose of projecting a real image on a screen with a laser beam, it is desirable to select only a narrow area by using an undiverged beam so that the area covered does not exceed a few millimeters in diameter. In this case, the real image consists of rays at small angles relative to one another. This increases the depth of field, allowing us to have a focused image over a long distance along the beam paths that form the real image. Many laws of geometric optics operate here, i.e. depth of field, resolution, etc.

Dynamic Range - Not only the locations of all the points on an object are reproduced in the hologram, but their relative intensity as well. Suppose our scene consists of sources B and C with B having the same intensity as A but with C being less intense than A (Fig. 9). We can assume that the mirrors formed between A and B are of higher reflectivity than those formed between A and C, due to the difference in fringe visibility.


3-D
Cbject
Reference
Smaller
hologram



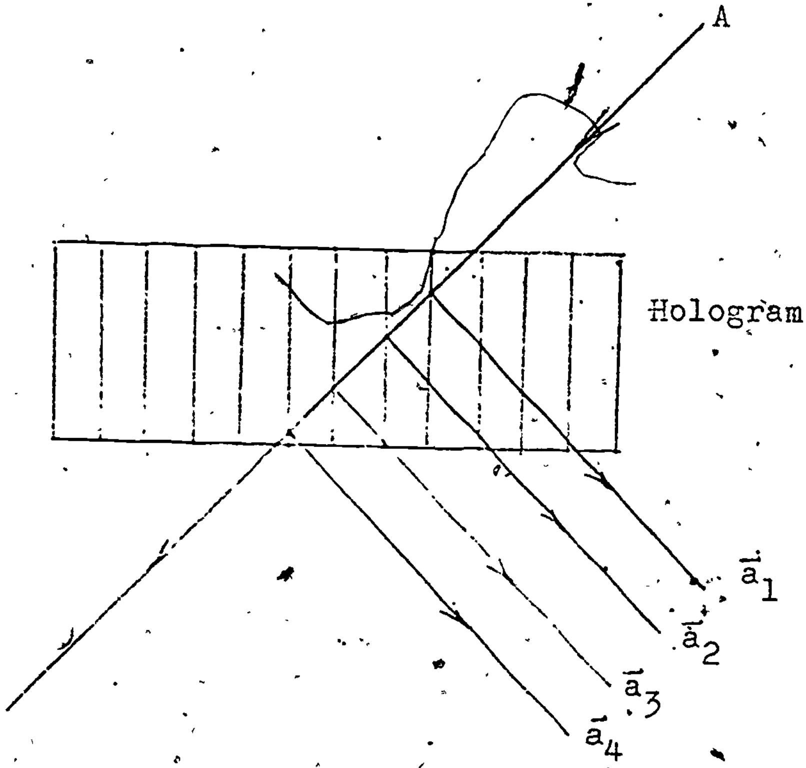
III-13

When this processed hologram is illuminated by A, points B and C are recreated by the reflected light from these surfaces in correspondence with their original intensity. Thus, a hologram can recreate total variations from faintly illuminated areas to glares.

Noise - As is true in all information transmission systems, the output always has noise added to it. Besides the so-called grain noise of photographic film, which is due to the scattering of light by the particles in the film, another source is called intermodulation noise. In Figure 9, not only are there interference patterns between A and B, and A and C, there is also a pattern formed between B and C (not shown). The latter pattern forms a set of hyperboloids that also intersect throughout the volume of the film but of much lower spatial frequency (fewer lines per millimeter across the surface of the film). This results in the scattering of light in arbitrary directions when the hologram is illuminated with the reference beam alone. When the scene consists of three-dimensional objects, every pair of points on the object creates an unwanted interference pattern. Therefore, the larger the object and the closer it is to the film plane, the more serious the intermodulation noise becomes.

Beam Ratio - To help minimize the effects of intermodulation noise, practical holography requires that the reference beam be of higher intensity than any point from the object. In practice, the intensity ration, as measured by using a diffuser in front of a light meter, between the reference and object beams varies from 1 to 1 to 10 to 1 for transmission holograms, the type so far discussed. This allows the mirrors to form between the reference and points on the object to be generally of higher reflectivity than those formed between any pair of points on the object. Also, the noise can be further minimized by having the smallest angle between the reference beam and any object beam to be greater than the largest angle formed by a pair of points on the object. This assures that the minimum spatial frequency formed by the object and the reference beam is greater than the spatial frequency of the noise. When the hologram is illuminated, the inter-modulation noise is diffracted to angles always smaller than the signal desired. In this way, even though we cannot eliminate the noise, we can isolate it.

Multiple Scenes - One of the most dramatic features of a hologram is that it is capable of recording more than one independent scene over the same volume to be viewed independently by changing the relative angle between the plane of the hologram and the reference beam. The phenomenon involved is Bragg diffraction and is understandable by the use of the model. For simplicity, Figure 10 shows a cross-section view of the interference pattern formed in the hologram by having two sources far away from the film and making equal angle with it. Thus, the hyperboloidal surfaces inside the emulsion approach being planes. The relative dimensions of emulsion thickness to λ are in close correspondence to physical reality. For example, the thickness of the film, typically from 6 to 15 microns, exceeds the distance between planes. Therefore, a ray originating from the direction of the reference beam suffers multiple reflection by successive planes when it penetrates the film. However, because of the inherent characteristics of this family of Hyperboloids, (recall Fig. 1), each successive reflection will have a precise phase shift of 2π, i.e., the optical path is increased by precisely λ in each successive reflection. All the reflected waves then are precisely in phase and therefore add in amplitude, resulting in a strongest possible wavefront


A
Hologram
$\vec{a}_1$
$\vec{a}_2$
$\vec{a}_3$
$\vec{a}_4$

representing the object beam. If the angle of incidence is deviated from the original reference beam relative to the hologram, all the reflected beams will have different phase differences and the resultant reflected wave is much lower in intensity. Quantitatively, we can say that in the case of correct illumination, the absolute value of all the amplitudes is $a_1, a_2, \ldots a_n$ add (being parallel vectors) and the intensity is $I = (|a_1| + |a_2| + \ldots + |a_n|)^2$. In the case of the misaligned illumination the phase shift of each successive reflection is different from 2π and $I^1 = (a_1 + a_2 + \ldots + a_n)^2$, so that $I \geq I^1$.

In practice, when the illuminating angle is significantly different from the correct angle, no image can be seen. This is precisely the manifestation of Bragg diffraction.

To create multiple scene holograms, one exposes the film with object O_1, stops the exposure, changes to a second object O_2, changes the angle between the reference beam and the film, and exposes the second time. Generally, each exposure is one-half that of the exposure for a single scene hologram, assuming no great change in object brightness. The resultant pattern recorded in the processed film is the equivalence of the superposition of two independent sets of hyperboloids, each corresponding to a given scene. During reconstruction, depending on the orientation of the hologram with respect to the reference beam, the wavefront of one or the other scene can be recreated. This is true both for the real and the virtual images.

Depending on the thickness of the film and the size and proximity of the scenes relative to the film and to the reference beam, different degrees of success can be achieved in minimizing cross talking. A great deal more detail concerning this is explainable with this model than space here allows.

<u>White Light Reflection Holograms</u> - From our previous example in Figure 10, it is apparent that if the hologram is sufficiently thick, it can be illuminated by white light. Only the waves of the original frequency can be successively reflected in such a way that the image waves are in phase. All the other colors are reflected with phase relations other than 2π and their intensity is drastically decreased. In reality, the actual dimensions of the film used, versus the actual spatial frequencies, does not allow this to work well. In general, a red light constructed hologram can be viewed with any monochromatic color. For example, for holograms constructed by the helium neon laser and then viewed with the yellow line from a mercury or sodium lamp, one needs to tilt the hologram so that its normal makes a smaller angle with the reference beam. In such a way, the optical path difference among various successive reflections is compensated so as to become in phase again. In general, the image recreated is aberrated. The degree of aberration is in correspondence with the geometrical properties of hyperbolic reflectors.

The ability of the hologram to discriminate color depends on the number of reflecting planes that a given ray of reconstructing light encounters. To maximize this number the film should be placed in a location between the object and the reference beams as shown in Figure 11. Since the separation between the successive hyperboloidal surfaces along the line joining the two sources is $\frac{1}{2}\lambda$, the usual 6 to 7 microns thick photographic emulsion would store up to twenty planes for red light. The image from such a hologram can be reconstructed from a point source of white light as that from the sun or a penlight, and offers a narrow color band selection. We can consider each surface as a hyperbolic mirror so that all light reflected by it will appear to come from the object point. Since each ray of reconstructing light penetrates through many

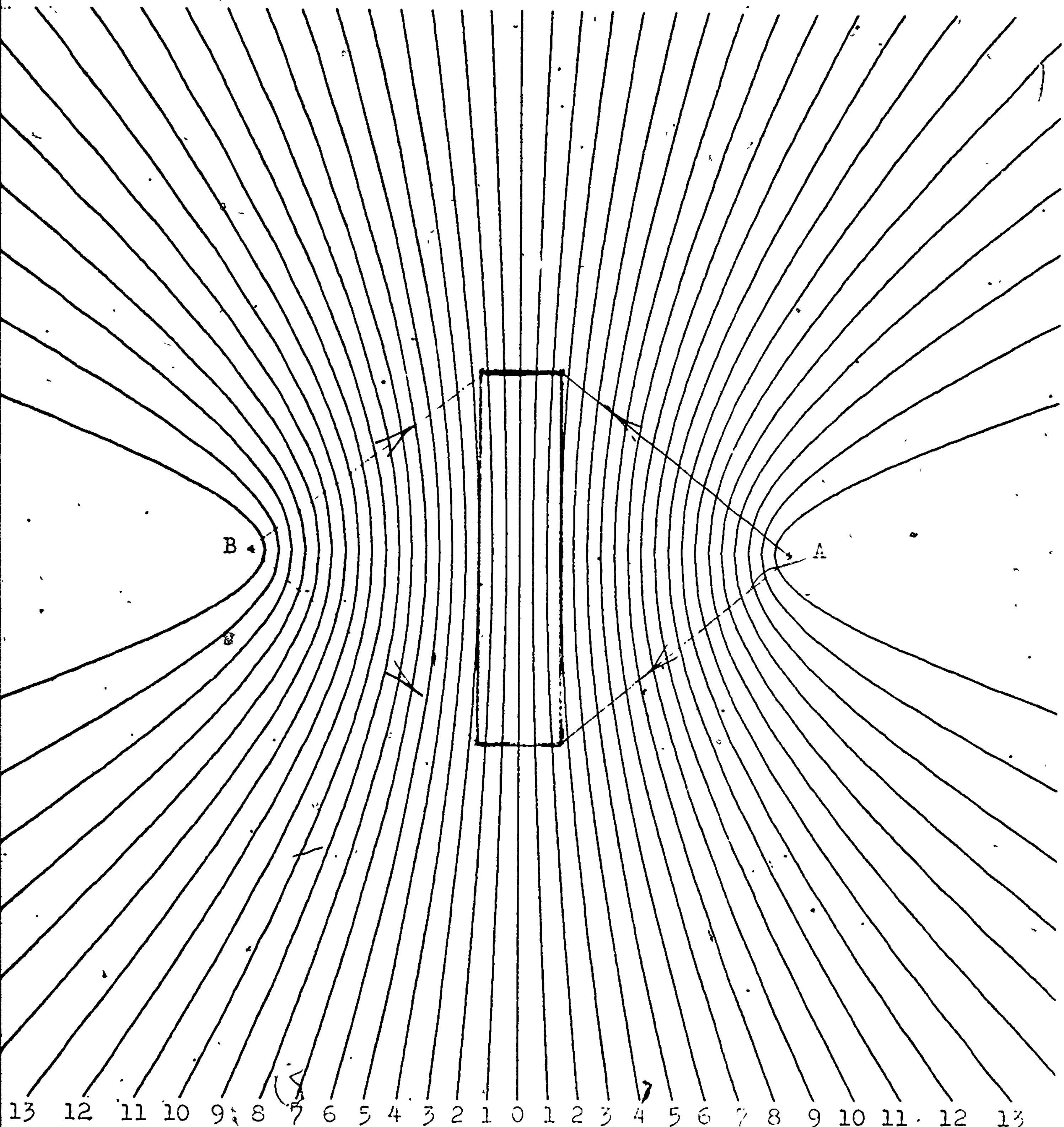


Fig. 11

planes, each reflection is in phase with all the others, the result is an intense reflection for the original color. The object point shown in Figure 11 can be a three-dimensional scene, illuminated by a separate beam of light from the laser. It is quite apparent that from this model, intermodulation noise will not be troublesome due to the fact that the surfaces formed by mutual points on the object are almost perpendicular to the set that we desire. Thus, it is understandable that the beam ration between the reference and the object beam should be near 1.

Holographic Interferometry - Consider a double exposure as represented by Figure 12. Here the object is located at B_1 during the first exposure and is moved to B_2, a distance in the order of λ, for the second exposure. The resultant hologram is a superposition of two sets of hyperboloids. As can be observed from Figure 12a, the two patterns coincide on the left-hand side of the hologram but fall in between one another on the right-hand side. As a realistic correction to our model (first perturbation?), we should realize that these surfaces, instead of being hard, infinitely thin planes, are actually sinusoidal in distribution. The result is that, when we view the hologram, we see a bright point located in the vicinity of the original object point from the left side of the hologram. From the right-hand side we see nothing, due to the fact that the two patterns add up to be a constant, resulting in no discernible pattern at all. If the object point had been displaced differently (to B_3 as shown in Figure 12b) its interference pattern would be shifted in such a way that the two patterns are in anti-coincidence on the left-hand side of the hologram but in coincidence on the right-hand side, and the situation then is reversed.

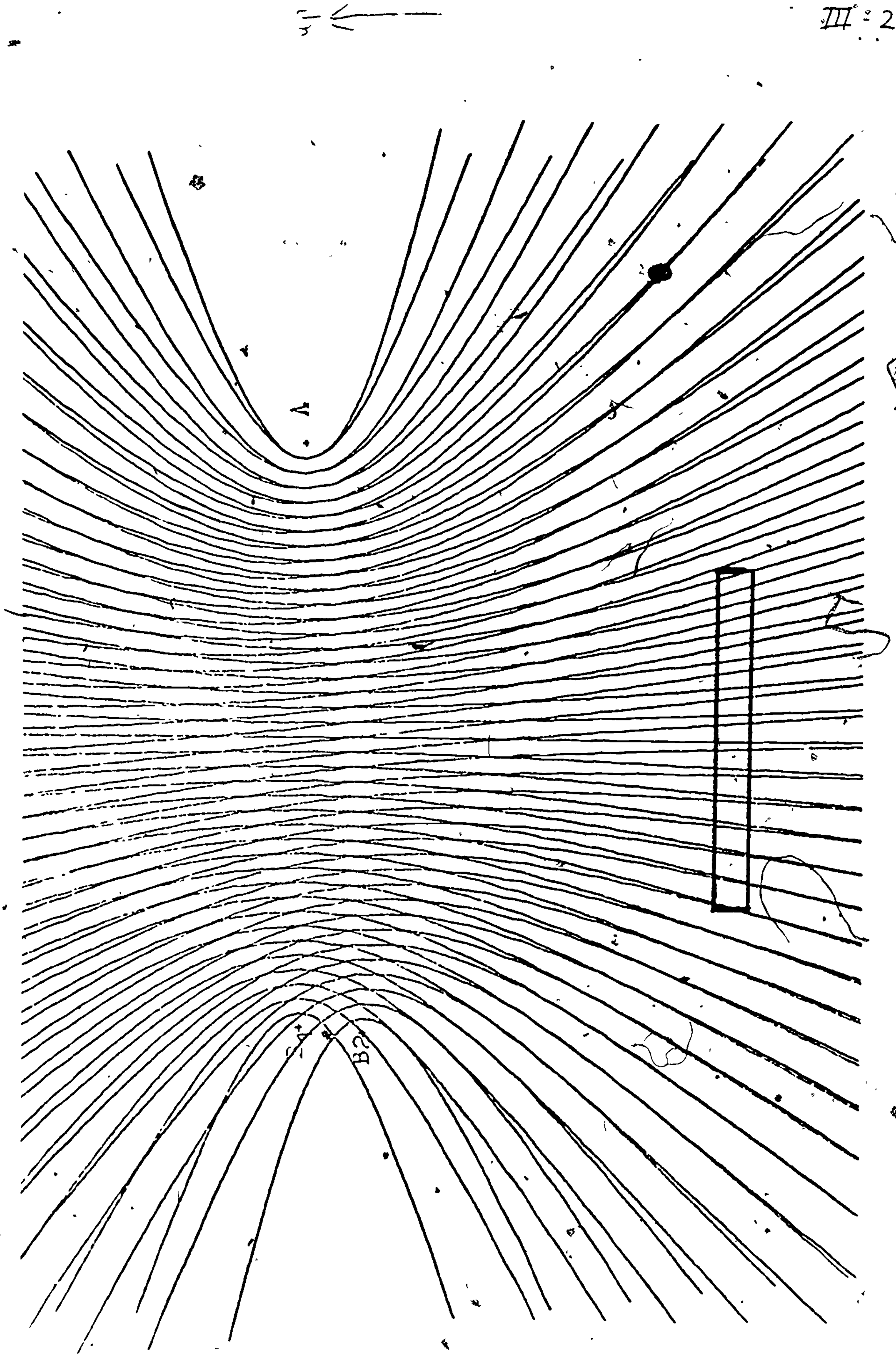


Fig. 12 a

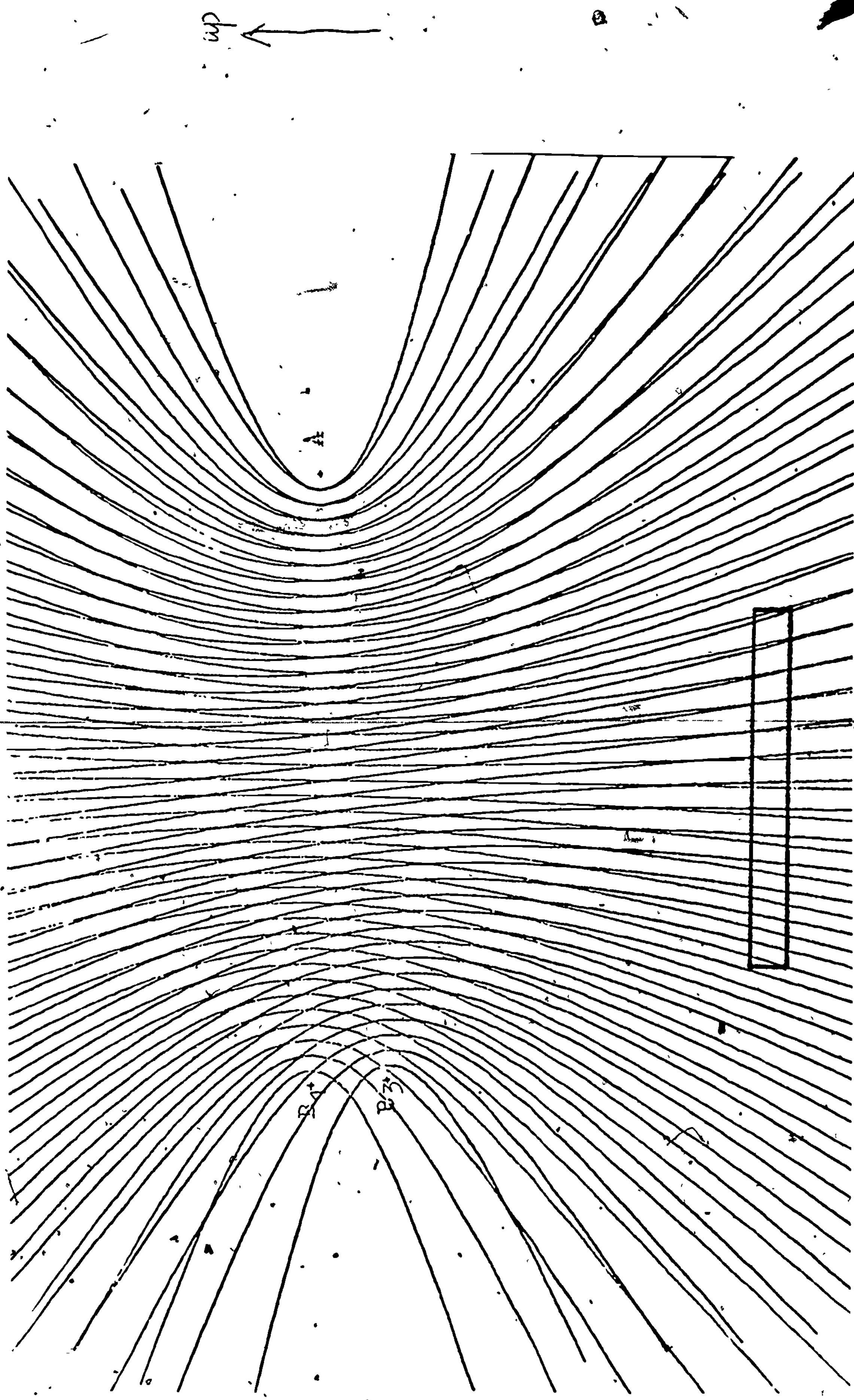


Fig. 12b

Therefore, for a continuously distributed object which is linearly displaced; we will see in general a set of straight black lines superposed on the image of the object. On the other hand, if the object is stressed, complex lines will be observed each of which represents loci of points in which the object beam suffered a constant phase shift.

Holographic Contouring - Dark interference lines can be formed on a scene that indicates points of constant elevation. This is done by exposing, either successively or simultaneously, the hologram with two different wavelengths of monochromatic light. Figure 13 shows the superposition of two sets of hyperbolas with the foci at the same locations, but with the number of interference orders differing by three, indicating a small wavelength difference. If the observer moves across this hologram, the object point will appear and disappear alternatively. If the object were extended in space and the observed looks through a given spot on the hologram, dark lines would appear on the object designating constant changes in elevation.

Coherence Length - (temporal coherence) - One of the basic techniques in making good holograms is to insure that the optical path of the object and the reference beam be equalized, beginning from the beamsplitter. In general, lasers operating without an internal etalon emit simultaneously more than one frequency. For example, the low cost helium neon lasers emit typically two to three different frequencies simultaneously. The frequency difference between the various lines is defined by

$$\Delta f = c/2L$$

where f is the frequency difference, c is the speed of light, and L is the distance between the two mirrors in the laser. When a hologram is exposed using a two-frequency laser, a contour is generated on the object if the size of the scene is sufficiently large. For the part of the scene in which the

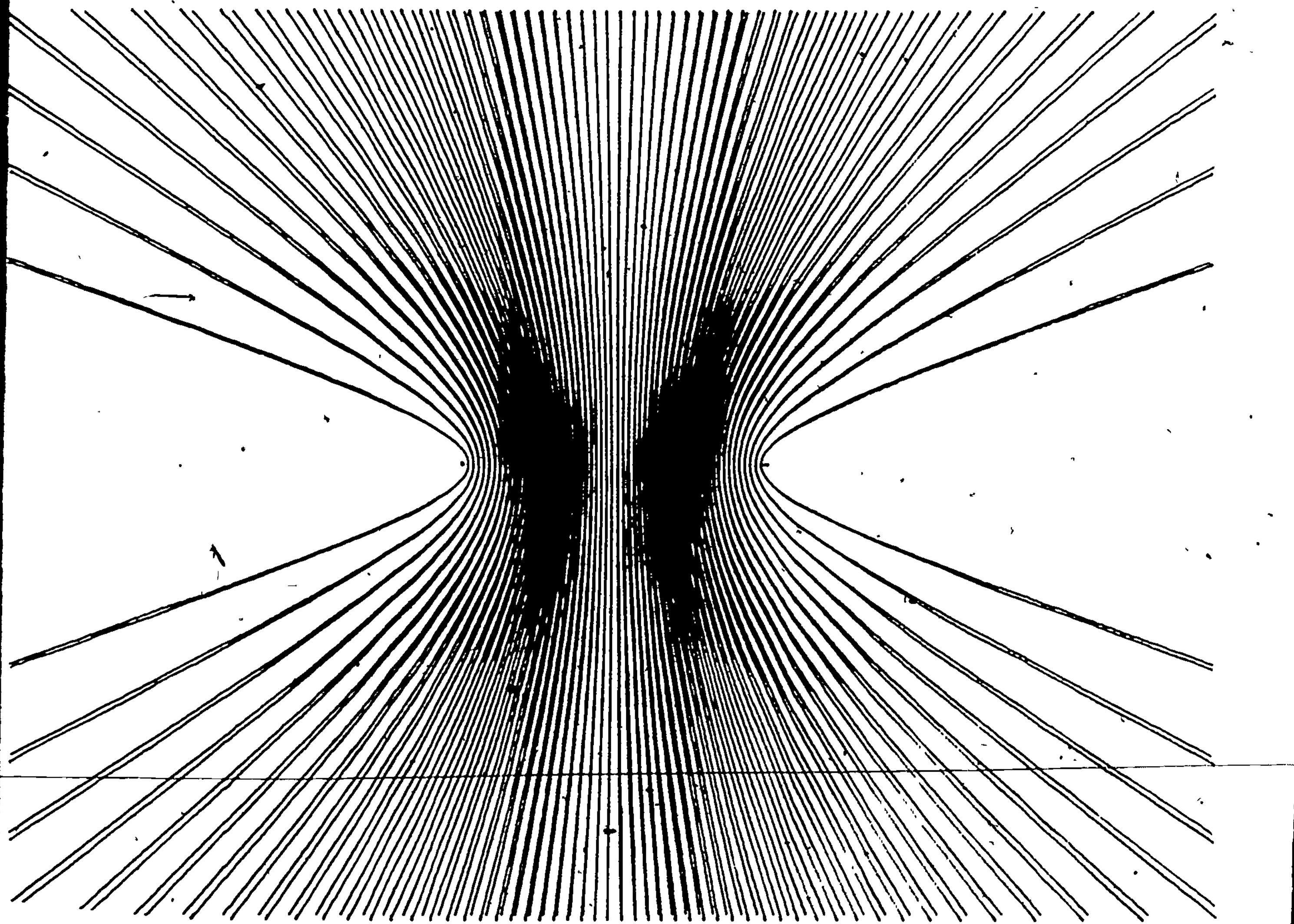


Fig. 13

optical path is equalized with the reference beam, the interference pattern resulting from both frequencies coincide on the hologram. The first dark fringe on the object represents the anti-coincidence of the two sets of fringes caused by the two frequencies. Therefore, for a sufficiently small object located at this first contour line area, no holograms will be made. Alternatively, if the location of the hologram is completely within the area of anti-coincidence of the two patterns, then, once again, there will be no net pattern recorded. Near the zeroth order, all frequencies are in coincidence. Therefore, even white light can form a distinct interference pattern, such as in the case of white light fringes of the Michelson interferometer.

<u>Spatial Coherence</u> - In all previous cases, we have assumed that the reference beam must always be a point source. We can invoke the model here to explain why it is unwise to do otherwise. Consider using a beam scattered from a piece of ground glass as a reference beam. In this case, the hologram exposed is equivalent to one which has a large number of individual reference beams from a variety of slightly different angles. Each reference beam forms an interference pattern in space slightly displaced from all the others. If the hologram thus recorded is later viewed with a point source, the image will appear to be blurred due to a variety of angular orientation of our imaginary mirrors. If the spot size on the ground glass is sufficiently large, the image can be blurred beyond recognition. In the case of the white light holograms, due to the close proximity of the hyperboloidal surfaces, no hologram will be formed in the first place.

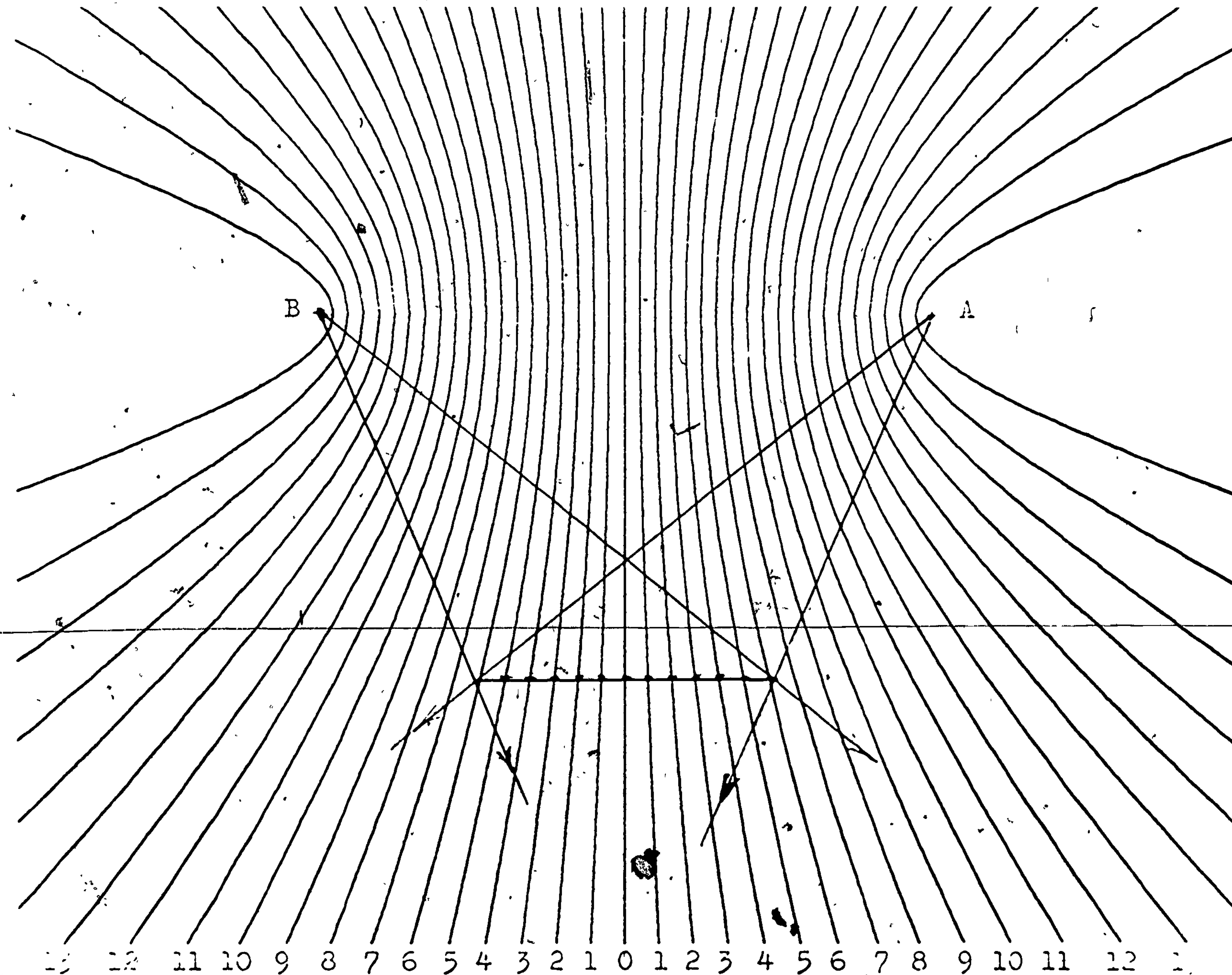
<u>Laser Speckles</u> - Anyone who has seen laser illuminated objects has noticed the speckled effect, i.e., a granular appearance on the surface. Furthermore, the size of the grains increase as one moves farther away from the surface. Our model will help to explain many of these observed

properties.

Consider a projection screen illuminated by laser light. Any pair of points on this surface will form an interference pattern represented by a family of hyperboloids in space (Figure 2). If we walk across the room while observing these two points, we walk across this pattern and observe alternately bright and dark spots. The closer the two points are, the coarser the pattern is. Also, the farther we are away from the points, the greater is distance between bright and dark areas. Since every pair form with each other a unique interference pattern of varying spatial frequencies and the illuminated area of the screen has a great number of points, the result is random distribution of a large number of different hyperboloids. Therefore, the granular appearance is inherent in the nature of the light. Additional characteristics contributed by the defects of the eye will not be discussed here.

CONCLUSION

As is true with all models, our geometric model for holography must break down at a limit. This limit is the "thin" hologram. A hologram is considered "thin" when the separation between the hyperboloidal surfaces exceeds the thickness of the emulsion. At this point, our model will start giving wrong answers. For example, a thin reflection hologram, according to the model, should give a white image when illuminated in white light; while, in reality, no image can be formed this way. Also, since there is no longer any Bragg effect, a transmission hologram should also be given a white image if white light is used for the reconstruction. The fact is that the image will be smeared in a continuous spectrum. On the other hand, the model has provided us enough background up to now to begin using diffraction theory for explaining holograms. We can now consider a hologram as a superposition of two dimensional gratings recorded on film due to a mutual interference of the reference with the object beams (Figure 14). By studying the properties of diffraction gratings, all the properties of a thin hologram can now be understood.



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CHAPTER IV

THE FOURIER DESCRIPTION

The previous chapter offered a physical model with which the holographer can visualize what he is doing in the laboratory. Far more elegant and useful is a formal understanding of holography. This involves a mathematical description mostly using Fourier analysis, and is well described in many excellent texts discussed in the last chapter. Here, we wish to present a qualitative model with which an instructor can discuss formalism with students in general and instill into them an appreciation of the elegance and beauty of physical science. Through the study of holography, we can demonstrate how the scientist operates between induction and deduction, between experience and formal ideas, and the interaction between nature and the mind. We do so by demonstrating that through physical observation, we can come to a set of formalisms which describes correctly what we see. Then, within the formal framework, we can work strictly on a mathematical level, and arrive at ideas that can be later translated back into physical reality.

From the pedagogical and educational point of view, this is singularly the most important message that holography can bring, independent from its usefulness as an optical medium. From past experience, the theoretical model presented here can be appreciated both by scientific and liberal arts students, independent of their level of mathematical understanding. We shall not attempt to make calculations; rather, we shall discuss how mathematics works for us and how it fits into the scheme of things in scientific pursuit. By using a basic set of holograms which can be constructed by the student or purchased, the ideas presented below can be made much more cogent and clear. Much of the presentation here will be in parallel with the previous chapter, but to accomplish a different purpose.

MATHEMATICAL BACKGROUND

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

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

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

Next consider Figures 2a and 2b . These represent a "beat note" which is obtained by adding two sine waves of different frequencies. If the curve f(x) is not symmetrical with respect to the horizontal axis, it merely means that there is a "dc" component $A(f_o)$. Analytically,

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

It can be shown that the square wave of Figure 3a can be obtained by summing all the sine waves designated in the Fourier spectrum (Figure 3b The instructor can actually draw a few of the sine waves on the chalkboard and add the amplitudes together point by point to prove this. The dotted line of Figure 3a is the center of symmetry of the wave, and its amplitude is represented in Figure 3b as the "dc" component. The f_o component is the "fundamental" of f(x), $3f_o$ is the third "harmonic"

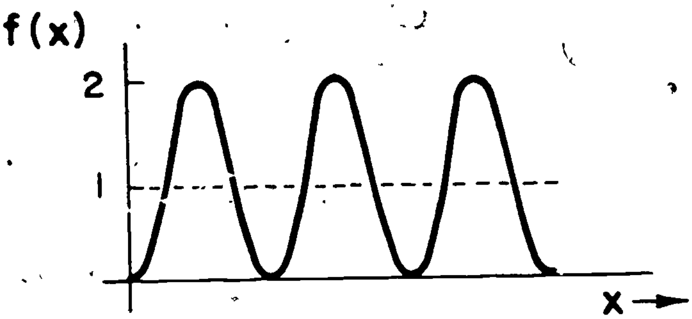

Fig. 1a

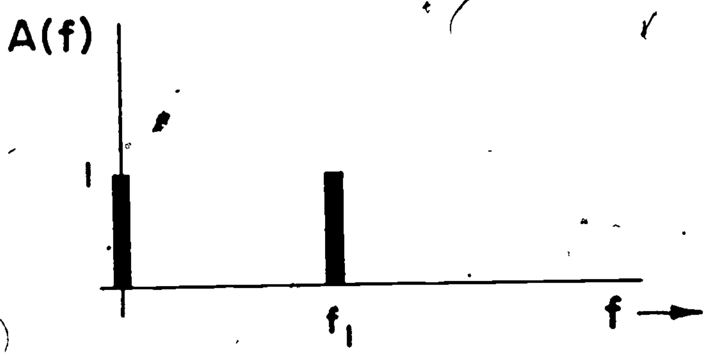

Fig 1b.

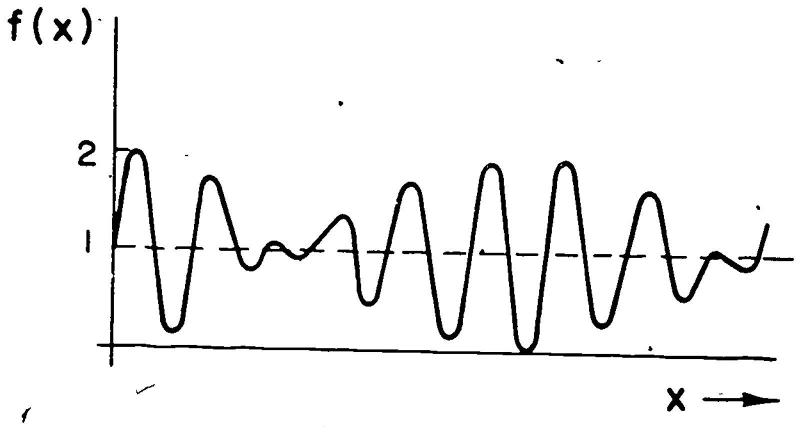

Fig. 2a

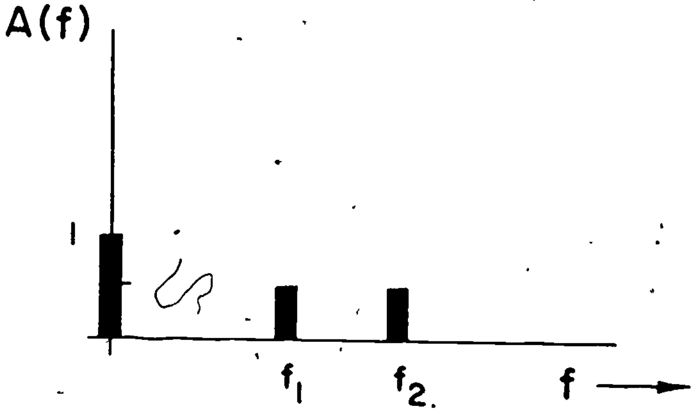

Fig 2b

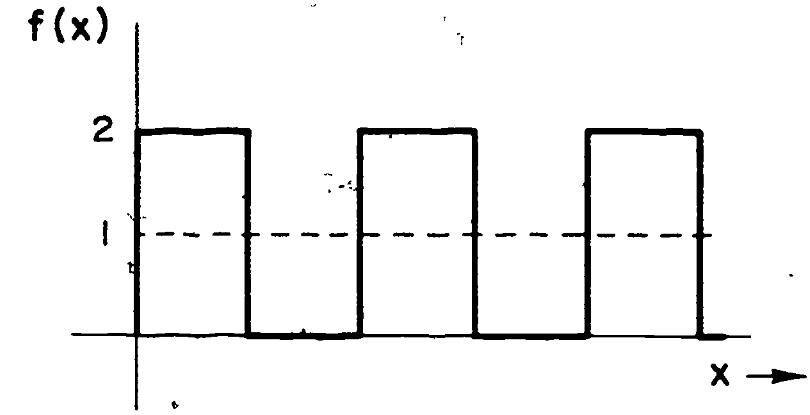

Fig. 3a

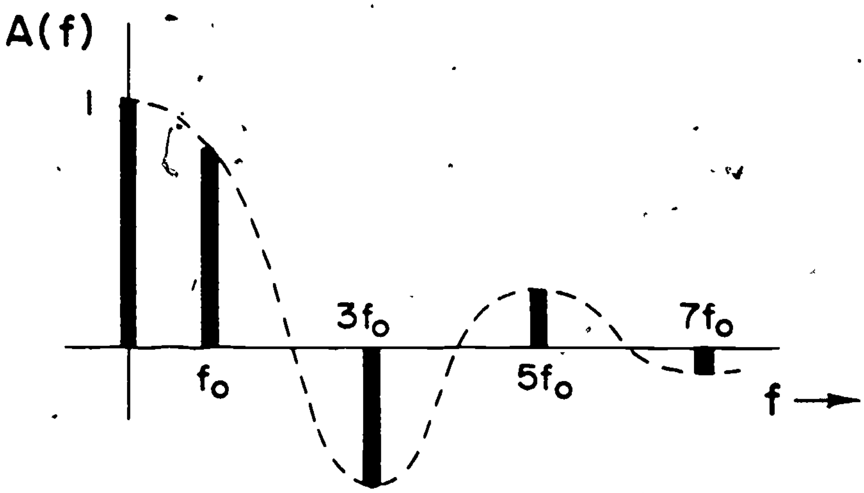

Fig. 3b

(or third order), etc. For a regular square wave, only odd harmonics are present. The dotted line on Figure 3b is the envelope of the spectrum which depends on the ratio between the widths of the top and the bottom of a cycle.

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

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

PHYSICAL DEMONSTRATION

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

1. <u>The sine grating</u>. The arrangement shown in Figure 4a is used to make the sine grating. A laser beam is split into two components and then recombined at an angle Θ to one another on a sheet of photographic film or plate. The intensity of the interference pattern across the plate

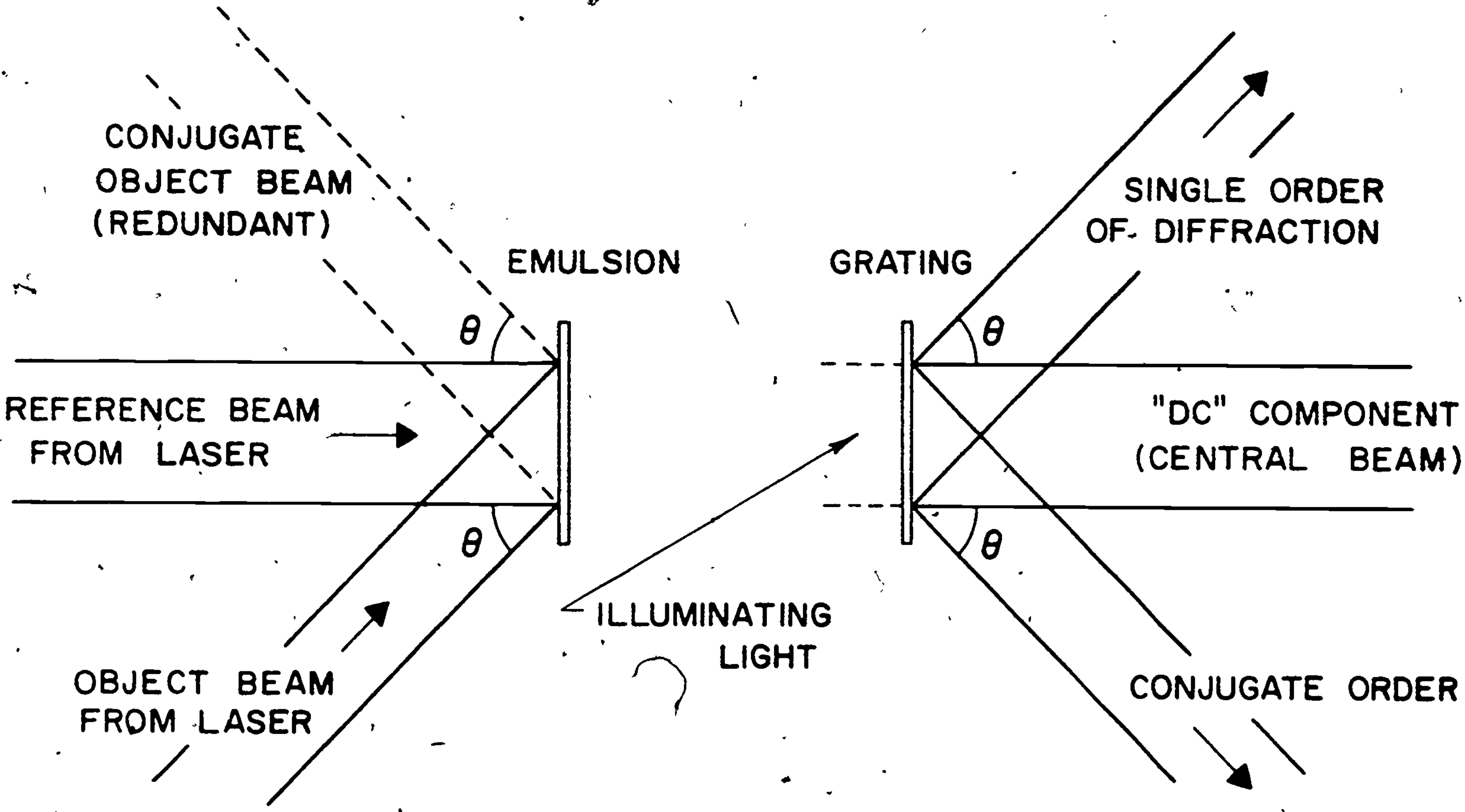
CONJUGATE
OBJECT BEAM
(REDUNDANT)
EMULSION
θ
REFERENCE BEAM
FROM LASER
θ
OBJECT BEAM
FROM LASER
ILLUMINATING
LIGHT
GRATING
SINGLE ORDER
OF DIFFRACTION
θ
"DC" COMPONENT
(CENTRAL BEAM)
θ
CONJUGATE ORDER

Fig. 4a

Fig. 4b

has a sinussoidial distribution, essentially the same as that caused by a Lloyd mirror or a Fresnel biprism. The spatial frequency increases with the angle Θ between the beams according to $f = \frac{\sin \Theta}{\lambda}$, where λ is the wavelength of the light. If the laser beam were split into three components, and the third component is recombined with the first two, as shown by the dotted line in Figure 4a , the interference pattern would not be significantly changed. Since the film does not "know" whether this component is present or not, the diffraction pattern from it has a symmetrical order on each side. (If the emulsion is thick, the situation will be different. This point will be discussed later.) One is called the complex conjugate of the other. This sine grating can be said to be a hologram of a parallel beam of light, or of a point object located at infinity, since the reconstructed wavefronts are the same as those used to expose the plate.

The basic principle illustrated is that the Fraunhofer diffraction pattern represents the Fourier analysis of the diffracting aperture, in our case a grating or a hologram. If we plot the transmittance (fraction of light energy transmitted) versus distance across the sine grating, the curve would look like Figure 1a , a pure sine wave having a certain number of cycles per millimeter (spatial frequency). As discussed above, such a wave has only one Fourier component, plus a "dc" term. When a beam of parallel and monochromatic light is diffracted by this grating, it can be seen that the diffraction pattern consists of an undeviated beam (the "dc" component) plus one order of diffraction on each side (Figure 4b

2. The beat grating. The diffraction pattern from a beat grating further demonstrates this principle. The transmittance curve in this case is represented by Figure 2a . As expected, the diffraction pattern

of this grating consists of two beams on each side of the "dc" beam, represented by Figure 2b. The beat grating is made in the same manner as the sine grating, with the addition of another object beam from a different angle. The pattern on the grating is just a superposition of two sine gratings of different frequencies. If more than two object beams are used, the beat pattern on the film gets more complex and the diffraction pattern from it merely reconstructs all the object beams. Furthermore, the object beams do not have to be in the same plane.

In the foregoing description, which holds for an arbitrarily small area in an arbitrarily thin emulsion, the film is performing a Fourier synthesis while being exposed, i.e., it adds together the individual sine waves caused by the interference between the reference and the object beam(s). The result is a complex periodic wave pattern. When monochromatic parallel light is incident on the processed film, Fourier analysis takes place and the light is spread into a configuration similar to that used to make the exposure. This is the process of wavefront reconstruction.

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

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

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

4. <u>The Gabor zone plate</u>. For simplicity, consider the interference pattern formed on the film by using the configuration shown in Figure Here, the object beam of Figure 5a has traversed a lens and focused at a point. This is equivalent to having light coming from a point object nearby. Notice that the angle, and therefore the spatial frequency, is dependent on the location on the film. For example, the spatial frequency on top of the film (Figure 5a) is $f_1 = \frac{\sin \Theta_1}{\lambda}$ and gradually decreases to $f_2 = \frac{\sin \Theta_2}{\lambda}$ at the bottom. Thus, the pattern subtends a finite bandwidth.

Imagine for a moment that the film is an infinite vertical plane, the light from the point object is isotropic, and the plane reference wave covers the entire film. Then there is cylindrical symmetry about a horizontal axis, and whose radial spatial object (dotted line, Figure The diffraction pattern on the film would be an infinite set of concentric rings, centered on the axis, and whose radial spatial frequency increases

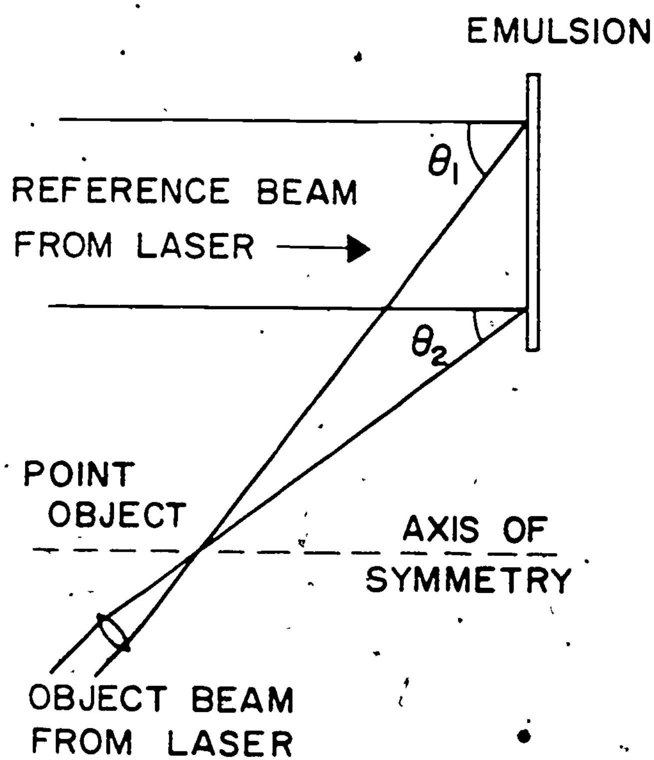
EMULSION
θ_1
REFERENCE BEAM
FROM LASER
θ_2
POINT
OBJECT
AXIS OF
SYMMETRY
OBJECT BEAM
FROM LASER

Fig. 5a

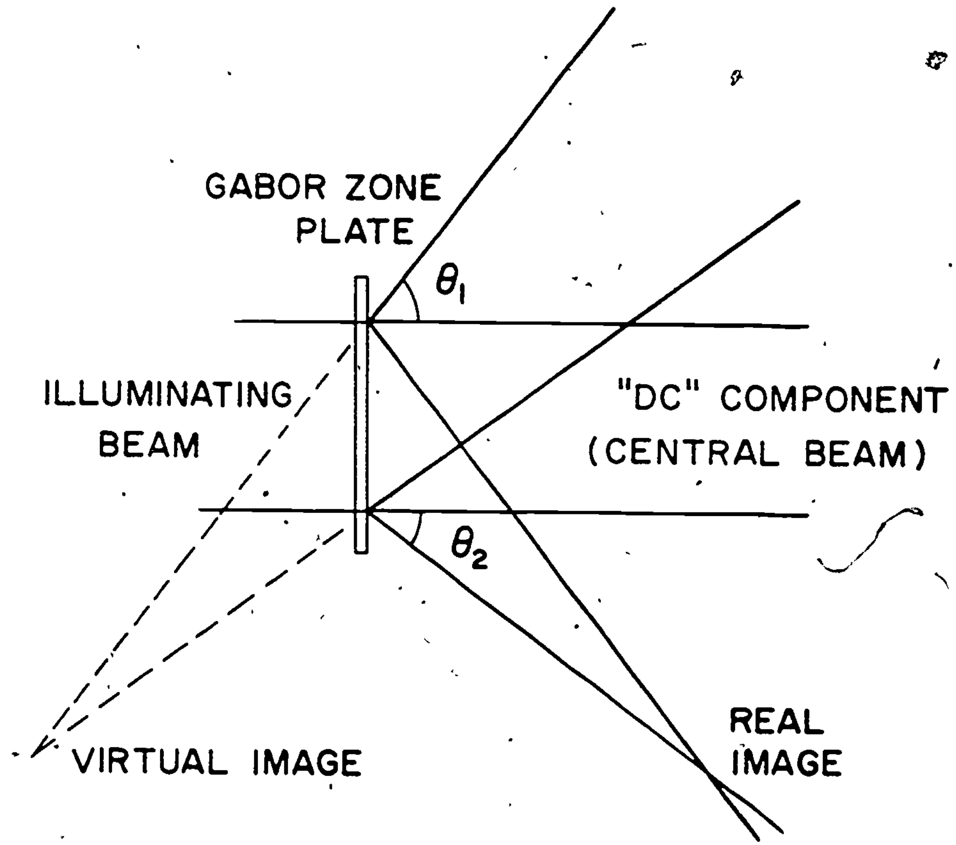
GABOR ZONE
PLATE
θ_1
ILLUMINATING
BEAM
"DC" COMPONENT
(CENTRAL BEAM)
θ_2
VIRTUAL IMAGE
REAL
IMAGE

Fig. 5b

with the radius. Since our actual film subtends a small off-axis section, the actual pattern formed on it is an off-axis section of the above set. If these rings were an alternatingly opaque and transparent set, they would form an ordinary Fresnel zone plate. However, this set is sinusoidal in character, and it will be given the name Gabor zone plate.

The reconstructed wavefront from this plate is shown in Figure One way to explain this pattern is as follows: Consider an area on the film small in dimension compared to the distance from it to the object point. During the exposure, both the reference beam and an element of the object beam arriving at this area can be considered to be parallel. Thus, locally, the interference pattern on the film is a pure sine wave. In the reconstruction, light impringing on any part of the processed film will have only one order of diffraction. However, the higher frequency regions have a larger dispersion, diffracting light to a larger angle. Therefore, light diffracted off the top of this grating diverges more than that diffracted from the bottom of the grating. By cylindrical symmetry, half of the diffracted light will converge to a point, forming a real image of the original point, while the other half diverges and forms a virtual image of the same point.

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

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

RELATIONSHIP BETWEEN SPACE AND TIME DOMAINS IN INFORMATION THEORY

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

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

1. Bandwidth. As described previously, a hologram has in general a continuous range of spatial frequencies. The bandwidth of the arrangement shown in Figure 5a is $\frac{\sin \Theta_2}{\lambda} < f < \frac{\sin \Theta_1}{\lambda}$. For a three-dimensional object, the bandwidth depends on the extreme angles between the reference beam and the rays from various parts of the object as they intersect on the film. Therefore, for a given reference beam direction, the bandwidth of the system increases with the physical dimensions and the proximity of the object and the film.

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

3. Filtering. A narrow bandpass filter can be used in radio to eliminate the noise in the carrier. Similarly, this can be done in holography. Consider Figure 6 . A parallel laser beam is reflected by a dirty mirror and then focused through a dirty lens. The unscattered beam converges to a point of typically a few microns in diameter at the focal plane. The images of the dust particles, however, will occur at the conjugate foci, not coincident with the focal point. Therefore, a simple pinhole located at the focal point will selectively pass the original parallel beam and stop the noise.

A meaningful demonstration on a dark field illumination in microscopes can be done using the simple arrangement shown in Figure 7 In this case, instead of the narrow bandpass filter described above, a narrow bandstop filter, i.e., a small blackened pinhead, is used. The laser beam is first diverged by a microscope objective and rendered parallel again with a larger lens. The object (a fine wire mesh, for example) is placed in the larger beam. The next lens converges the undiffracted "dc" beam into a point, which is blocked out by the pinhead. The diffracted light, however, is focused at the screen, placed at the conjugate focal plane to the object. An image of the object will then be seen without the bright direct light. By carefully moving the pin along the optical axis of the system, phase reversal can be seen as various orders of diffraction are cut off.

4. Fidelity. The amplifier and speaker system in radio is considered "Hi-Fi" if it has a wide passband without distortion. This is also true in optics. A larger lens has better resolution (fidelity) than a small one because it gathers a larger number of orders of diffraction (more harmonics) from the object and recombines them at the focal point. The lower limit of resolution is realized when the

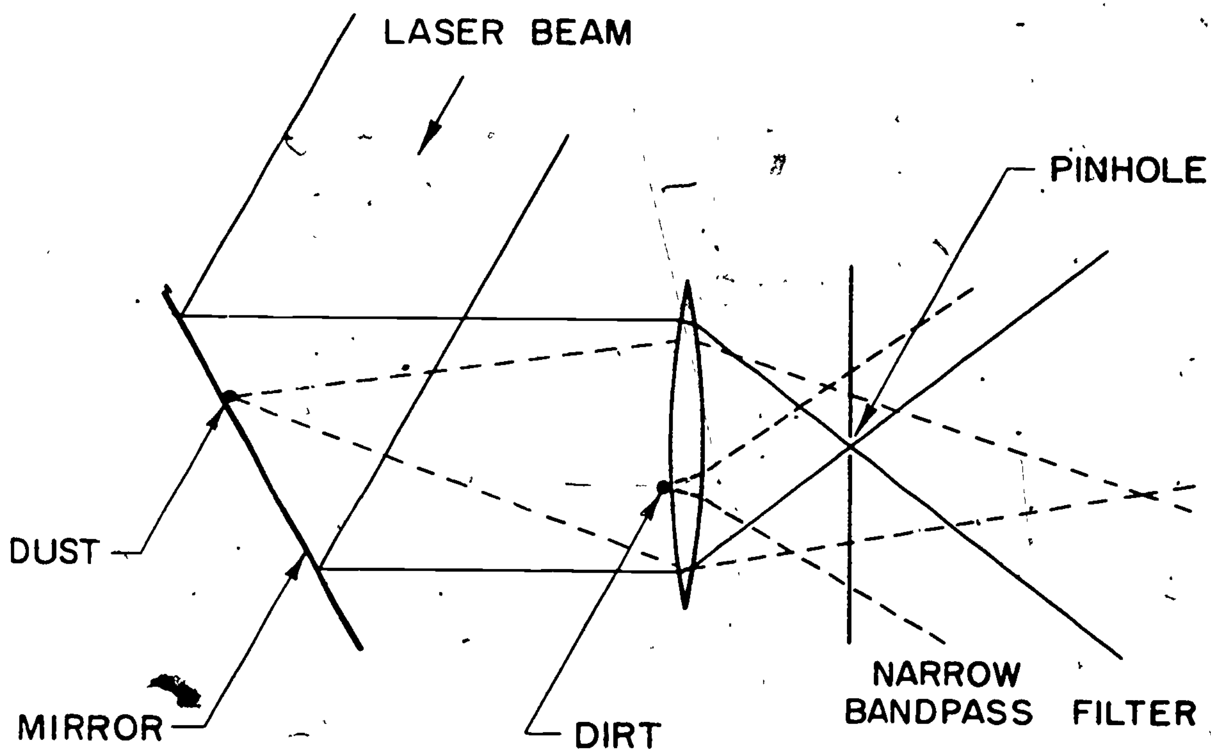
LASER BEAM
PINHOLE
DUST
MIRROR
DIRT
NARROW
BANDPASS FILTER

Fig. 6

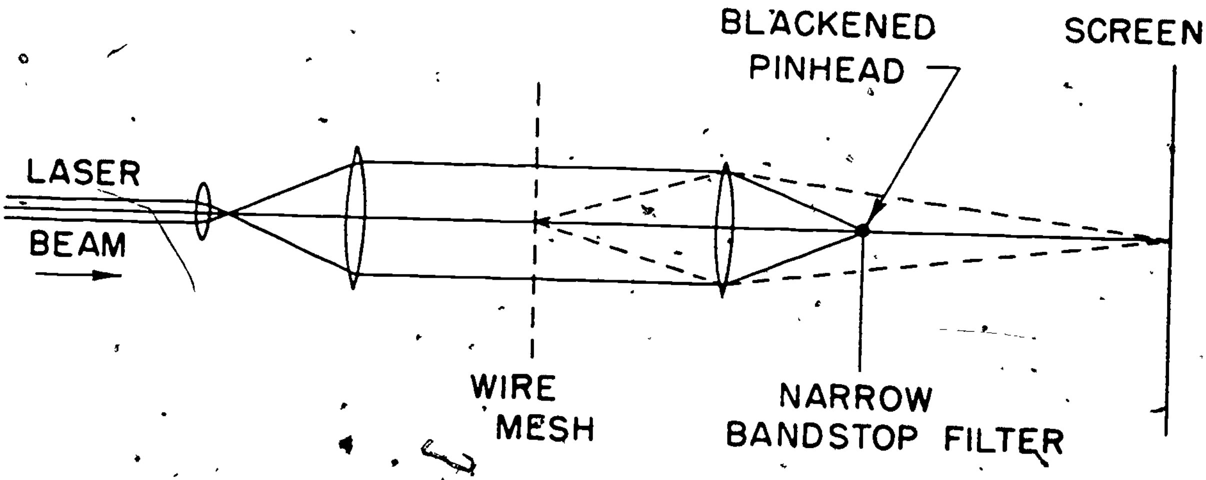
BLACKENED
PINHEAD
SCREEN
LASER
BEAM
WIRE
MESH
NARROW
BANDSTOP FILTER

Fig. 7

aperture is so small that only the "dc" component gets through, which carries no information. The lens here is performing a Fourier synthesis and a Fourier analysis all at once.

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

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

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

(a) Sideband suppression. Figure 8 depicts a more realistic picture of a hologram construction because it shows the emulsion having a finite thickness. For example, 8E75 plates have emulsion thickness of about 6μ. For simplicity, consider two waves interacting on the emulsion as shown, where the dotted lines indicate the crest of the waves. On the surface a sinusoidal diffraction pattern occurs with

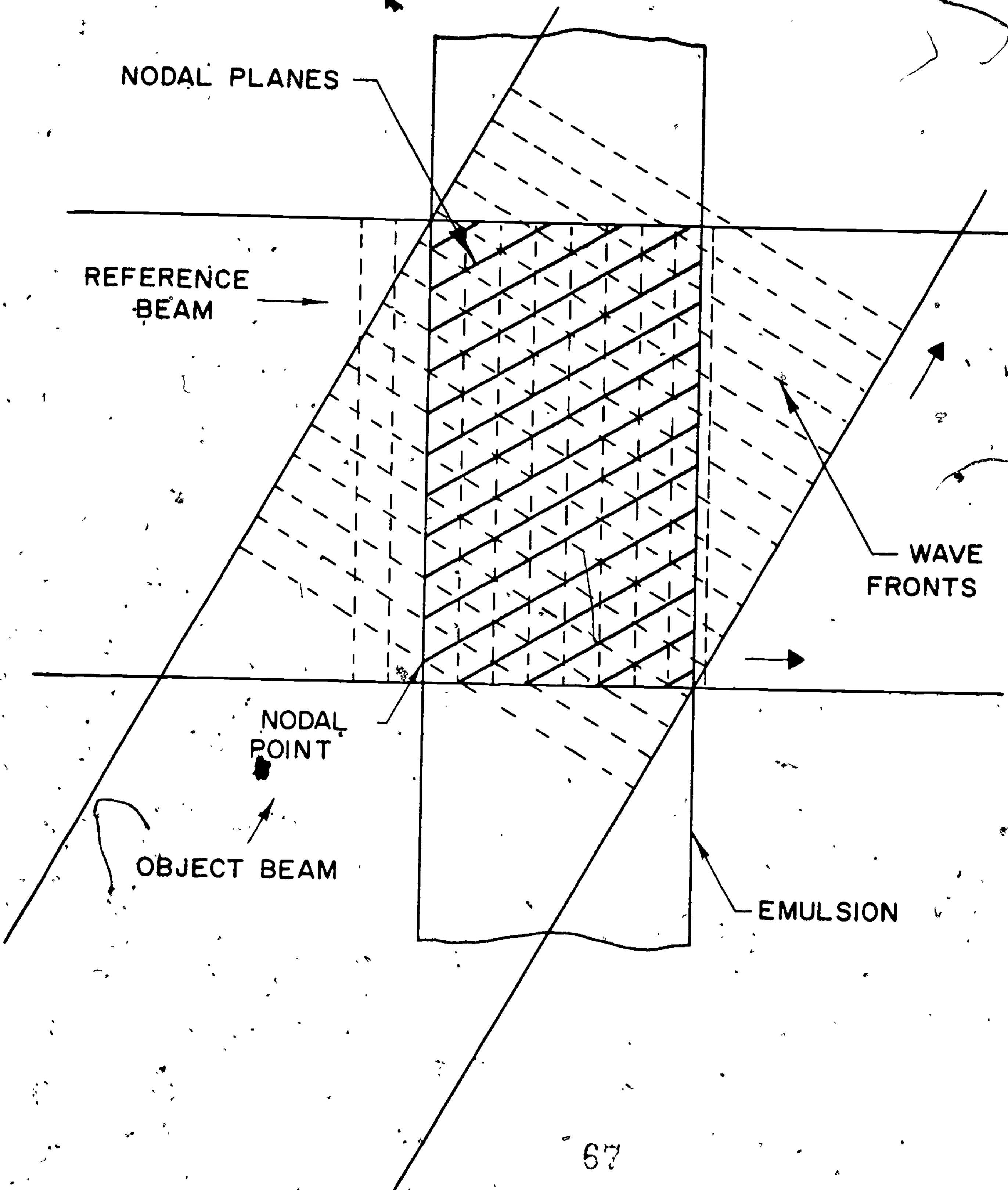
NODAL PLANES
REFERENCE BEAM
WAVE FRONTS
NODAL POINT
OBJECT BEAM
EMULSION

Figure 8

antinodes located at lines (into the drawing) where the crests meet. On the plane immediately behind the surface the same pattern occurs but is slightly shifted upwards. As the waves travel through the emulsion, nodal planes are formed, as shown by the heavy diagonal lines. When the emulsion is exposed and processed, these darkened planes behave as venetian blinds and suppress one of the sidebands. The effectiveness of the suppression depends on the emulsion thickness and density after development. If the plane object beam is substituted by a three-dimensional object, and a hologram is made, the real image is suppressed, but not lost. By turning the hologram backward, which reverses the direction of the blinds, the real image can be projected onto a screen and the virtual image is suppressed. In practice, this can be done easily by illuminating the backward hologram with a narrow laser beam. The small spot of the hologram used causes a sacrifice in resolution, but depth of field is gained in the projected image.

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

At this point we can utilize the fact that the space domain has three dimensions, whereas the time domain has only one. When one looks out at night through a square mesh wire screen window at a street lamp, one sees a diffraction pattern resembling a cross -- there are many orders of diffraction both in the vertical and the horizontal directions.

This is so because the screen is a two-dimensional square wave, which has many Fourier components. If the transmittance of the screen had been sinusoidal in both directions, there would be a total of four sidebands, located symmetrically around the lamp. This means that after the initial exposure during a hologram construction, the photoplate can be rotated 90 deg. at a time until four completely different scenes are recorded, one on each sideband. In fact, any number of independent scenes can be recorded in principle by making a smaller rotation on the photoplate after each exposure, the limit being the overexposure of the emulsion and the occurrence of cross-talk between adjacent scenes. Overexposure, however, can be remedied to a degree by bleaching the finished hologram in potassium ferricyanide or mercuric chloride, changing the "amplitude hologram" into a "phase hologram." The latter is similar to a transparent grating having on it a pattern of variations in thickness and/or index of refraction.

7. Tube characteristic versus film characteristic. Everyone is, to a degree, familiar with the characteristic curve of vacuum tubes and how it affects the transmission of information in radio. A strikingly similar consideration occurs in holography. Figure 9 shows the characteristic curve of a typical emulsion. We can consider the reference beam as a "dc bias" which exposes the emulsion uniformly to the center of the linear region of the curve (vertical dotted line) and the object beam as a modulation. For a given emulsion, the total exposure as well as the ratio between the intensities of the reference and object beams must be correct in order to transmit the strongest signal without distortion. For 8E75, the correct intensity ratio between the reference and the object beams is approximately 6 depending on the bandwidth and other factors to be discussed later.

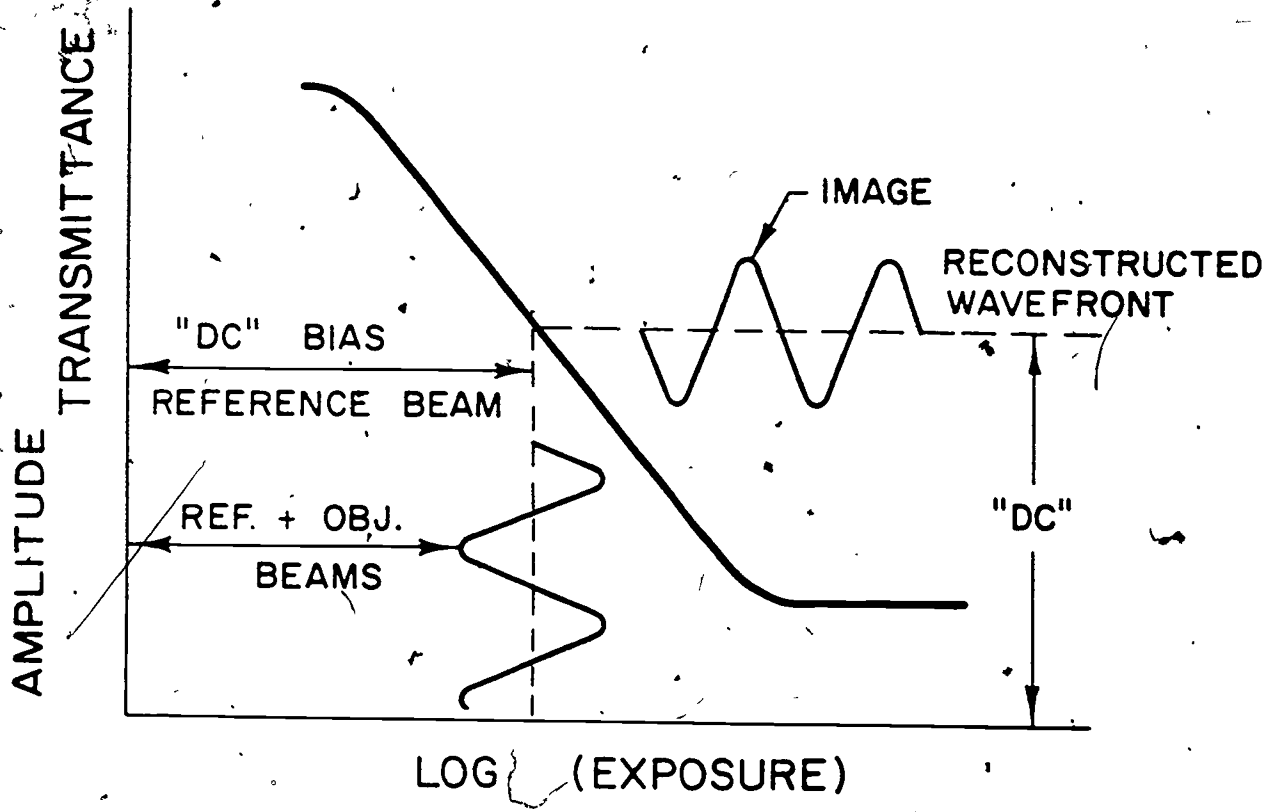
IMAGE
RECONSTRUCTED WAVEFRONT
"DC" BIAS
REFERENCE BEAM
REF. + OBJ. BEAMS
"DC"
AMPLITUDE TRANSMITTANCE
LOG (EXPOSURE)

Fig. 9

If the film is overexposed or overmodulated, higher harmonics can be demonstrated if a hologram is made with a small reference beam angle relative to the object. The result is that second and third order diffraction can be seen, showing non-linear response.

RELATIONSHIP BETWEEN THEORY AND PRACTICE

The preceding demonstrations sufficiently show that the Fourier description fully applies to holography. At this point, independent of the background of the students, it is fruitful to both show and discuss how one might obtain physical ideas from pure theory. It is both dramatic and informative here if the instructor arbitrarily pulls out some mathematical theorems from any standard text on the mathematics of Fourier analysis. For simplicity, following is a one-dimensional pair of Fourier transforms where x denotes the distance across a one-dimensional hologram and ω is the spatial frequency in units of lines per meter.

$$f(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} A(\omega)e^{-i\omega x}\, d\omega$$

$$A(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(x)e^{i\omega x}\, dx$$

This theory is developed well over a century ago and we wish to show that it applies to our present subject. We proceed by arbitrarily selecting theorems derived from this transformed pair and ask the following question: What does this mean physically?

Take the First Shift Rule: If $A(\omega) \leftarrow f(x)$,

then $f(x-b) \rightarrow e^{ib\omega}A(\omega)$.

Physically, this means that if x is changed by a constant distance, b, the Fourier transform (in the frequency domain) the function is not at all changed except by a phase factor. If the transform is squared, which represents intensity rather than amplitude, the phase factor drops out, leaving the function $A^2(\omega)$ unchanged. This can be physically demonstrated by moving a sine grating across a beam in a direction strictly perpendicular to the lines on the grating, and show that the diffraction pattern on the screen is not at all changed. This idea resulted in a very useful application in RCA's Selecta-Vision system which uses holography to record television programs. Essentially, a sequence of holograms is made of corresponding sequential frames of a standard motion picture. The projected image from the hologram will be completely stationary so long as a laser beam is scanning across a given hologram. As it jumped to the next hologram, the image is abruptly changed and then again remains stationary until the next hologram is scanned. This means that the holographic record can be transported at constant speed, unlike motion pictures, which require beam chopping and uneven motion.

Another illustrative example is the Convolution Theorem:

$$\text{If } f_1(x) \rightarrow A_1(\omega) \text{ and } f_2(x) \rightarrow A_2(\omega)_1,$$
$$\text{then } \int_{-\infty}^{\infty} f_1(\tau) f_2(x-\tau) d\tau \rightarrow \sqrt{2\pi}\, A_1(\omega) A_2(\omega) .$$

Thus when one function is convolved with another, it is equivalent to a simple product of their transforms in frequency space. Figure 10a shows an application of this idea. If an object is located behind a highly warped piece of glass and a hologram is formed this way, the subsequent viewing of the hologram will yield only the deformed image. We here illustrate the convolution between the light arriving from the object with the screen. The image can be retrieved by a process of de-convolution. This is accomplished by projecting the reference beam precisely backwards through the hologram (Figure 10b). The diffracted light goes backward through the warped glass, which decodes the image and forms an undistorted image on a screen located at the position of the original object.

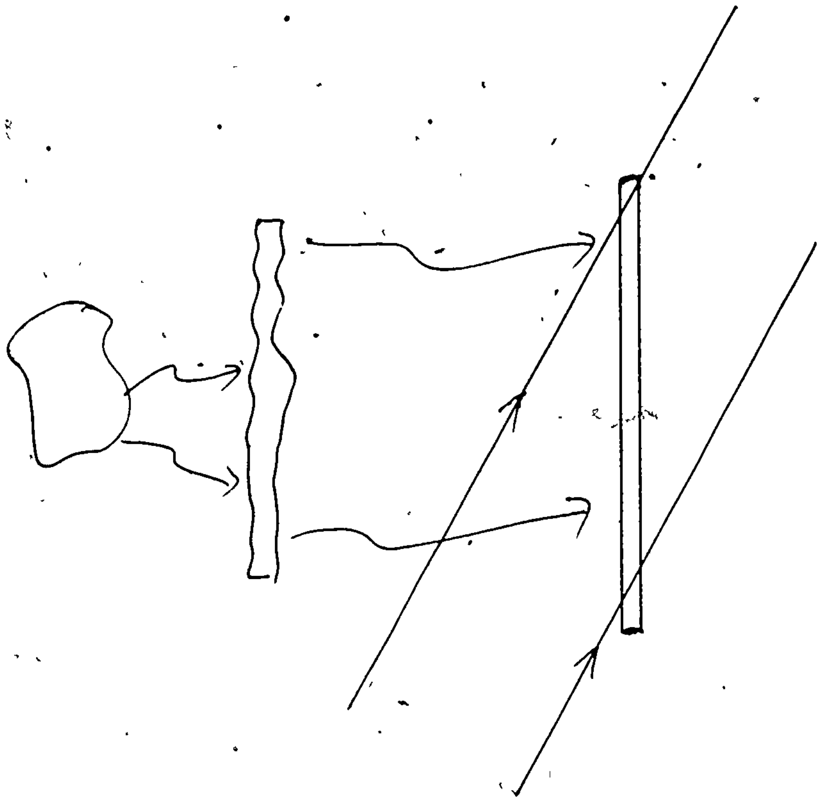

Fig. 10a

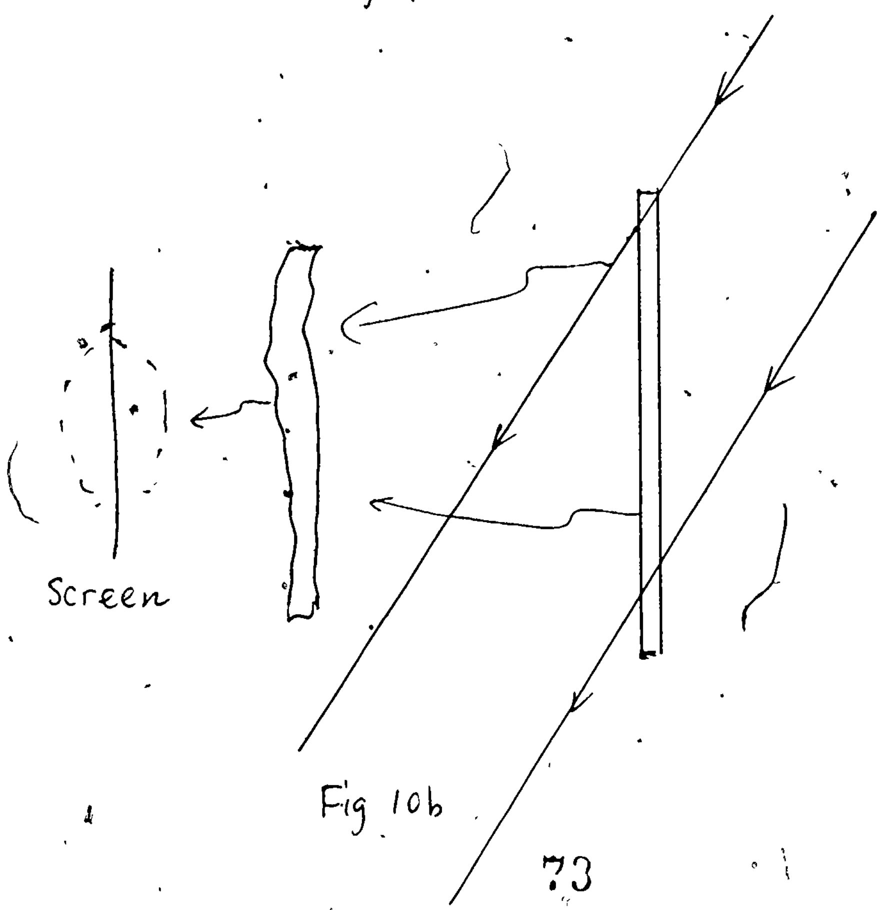

Fig 10b

The preceding are but two simple examples of this. The student will be highly enlightened if he goes further and checks on other theorems to find physical meanings. Indeed, it can become a game, if one takes an electronic text and substitutes at the location of the time variable with a space variable and tries to conjure the physical meaning arrived from this change.

The existence of the symmetry between the time and space domain in information theory is not accidental. It is part and parcel, in fact, of the way in which waves behave. And all these ideas have been summarized in a nutshell over a hundred years ago by James Maxwell. Indeed, the physics of communication systems, whether they operate in the time or space domains, are derivable from the basic Maxwell equations. The realization and the appreciation that the human mind can perform such grand analysis and synthesis is sufficient to put religion into holography.

CHAPTER V

Material Requirements

The title of this chapter implies that what follows will be merely a list of hardware and software. Actually, a detailed understanding embodies an inexhaustible amount of physics from the theory and operation of mirrors and lenses to the quantum theory of the laser. Minimally the student needs to understand the simple theories of reflection, refraction, and simple lenses. More advanced studies involve polarization, the electromagnetic theory of reflection and transmission from dielectric and metallic surfaces, operation of the laser, as well as the chemical processes involved in developing the film.

One of the greatest inducements to include holography in the science curriculum is its low cost. A great deal can be done with a total budget of approximately \$250. For schools that already possess a suitable laser, a budget of \$150 will suffice to start a program in holography. Furthermore, the material listed below is easily obtainable and can be assembled with minimal skill, using common tools.

On the other extreme, sophisticated components are now available which can exhaust any budget. The philosophy in this writing will be to emphasize the inexpensive methods. Assuming that once money is available, one can always easily educate himself to spend it.

As is usually the case, greater expense does not insure proportionate success. For example, a simple windowpane variety glass makes a better beam splitter than a host of much more expensive items. Much depends on the ingenuity and the depth of understanding in the function of each component.

What follows is a basic list of material required, with some general emphasis on minimal requirement and expense:

General Hardware

For a sandbox system, most optical components can be mounted by attaching them with modeling glue to 2-inch diameter PVC pipes obtainable from construction companies or hardware stores. For systems with a hard-surfaced table, it is useful to have a good collection of rods, clamps, right-angle clamps, and stands.

Vibration-Isolated Table

A low cost, versatile holographic table can be constructed by using 1-inch thick plywood (or any well-aged lumber), and construct a 6 x 8-inch deep box. The other dimensions might be 2 x 3 feet or 3 x 4 feet. In general, it should not be larger than what can go through a lecture room or laboratory room door, but large enough to accommodate the laser to be used. In general, this type of system should not exceed 5 feet in either dimension because stability will begin to suffer.

This table is then filled with white silica sand, 5 to 6 inches deep. This type of sand is generally used for ash trays and is obtainable from construction companies or your janitor.

Underneath this sand-filled box should be two to four 12 to 20-inch diameter inner tubes inflated to their normal sizes. They are go-cart or home tractor inner tubes and are available from NAPA dealers as well as Sears Roebuck & Company.

For general versatility, this whole system - inner tube and sandbox - can rest on a movable laboratory table so that it can be wheeled from lecture demonstrations into laboratories.

One of the greatest advantages in using the sand system is that almost all the components to be used in it will be mounted on PVC pipes and will <u>not</u> be useful for any other purposes. This avoids scroungers that are abundant in every science department.

However, an equally suitable and generally more useful table can be constructed by resting on inner tubes, as mentioned before, any type of hard and strong surfaces. This includes steel plates or even cement slabs. In general, mass and rigidity are desired. For this type of table, components can be mounted on rods and clamps for height adjustment.

On the other hand, PVC pipes used on the sand table will hold their position easily, at any angle, since the inside is filled with sand.

<u>Laser</u>

Although lasers are now obtainable with outputs in any visible color, the time-tested lowest cost and highest reliability laser is the helium neon (HeNe) laser. The cost starts from $110 and up. Although the lowest cost one will make simple holograms, the general rule is that the greater the output, the greater variety of holography can be performed. In general, specify a laser which operates in the TEM_{00} or uniphase mode. This can be checked by passing the red light from the laser through any type of simple lens and observe the enlarged spot on a screen. There should be a well-defined round spot with the highest intensity at the middle and a smooth decrease toward the edge. Move the lens slightly to discern dust diffraction patterns from the beam structure. The laser should be rejected if it has a dark spot in the middle or if the beam consists of several spots.

Lasers of this type can be obtained with polarized or unpolarized outputs. If a choice is available, the polarized output is generally more useful; although either type will make holograms.

Front Surface Mirrors

Only front surface mirrors should be used for holography. If a bathroom-type mirror is used, the front surface will reflect a portion of the light as well as the back surface, causing two beams which interfere with each other. In general, a minimal system requires two small (below 1 x 1 inch) and one large (4 x 5-inch) mirror.

The quality of their surfaces is important and can be checked simply. With a beam expanded by any lens, reflect it to a distant screen with the mirror under test. The diffraction patterns caused by dust and scratches on the lens or the mirror can be discerned readily by slightly moving the two components. There should not be additional diffraction patterns, observed as mottled patterns, caused by scattering of the surface.

The mirrors can be mounted on PVC pipes or glued to a metal plate on which threaded rods can be attached.

Beam Splitter

A surprisingly versatile beam splitter is a piece of double weight windowpane glass. It reflects approximately ten percent of light incident at 45° and transmits most of the rest. By using a sufficient thickness, the two reflections from the two surfaces will give well separated laser beams. The weaker one can be sacrificed by blocking it off. This glass, which need not be much bigger than 2 x 2 inches, can be again mounted either on a PVC pipe or held in a lens holder. Commercially a great variety of beam splitters are available in the forms of cubes, segmented discs, graduated discs, and cemented polarizing crystals.

Film Holder

For film below 4 x 5 inches, it can be held between glass plates equal or larger in size and clamped at the edge with black steel paper clamps obtainable from stationery stores. For a sandbox system, the two glass plates used should be larger than the film so that the extra glass can be directly stuck into the sand for positioning. For hard-surfaced tables, the clamps, when moved to the bottom of the glass, can serve as stands to hold the film vertical. To make larger holograms on film, vacuum platens are required.

Lenses

To spread out the beam so that it covers an object to be illuminated or a piece of film, positive or negative lenses can be used. Since we desire generally to spread the beam out in a minimal distance, lenses with the shortest focal lengths are desired. For low cost systems, double concave lenses with minimal diameter and focal length can be used. For more sophisticated systems, microscope objectives with powers of 10 or 20 are suitable. In general, at least two lenses are required for each system.

Spatial Filter

In general, all optical components have dust or scratches on them. This causes laser light to diffract, resulting in noticeable patterns in the beam. Althouth this does not prevent one from making a hologram, it does cause spatial noise. To minimize this effect, a positive lens is used, with a suitable pinhole located at the focal point. The latter cuts off all scattered light and permits only the direct beam originated from the laser to go through. For learning purposes this device is not necessary initially, but becomes desirable when quality in the final hologram becomes crucial.

Most commercially available spatial filters use a combination of a 10-X or 20-X microscope objectives in combination with a 20 or 10 micron pinholes, respectively. In general, the microscope objective is moved with a micrometer along the beam direction while the pinhole is microscopically positioned in the other two directions.

Diffuser

For even illumination of large scenes and for the artistic effect of soft lighting, a diffuser in the form of a 4 x 5-inch piece of ground or opal glass is used. Once the beam has been expanded by a lens to a diameter exceeding one centimeter, it can then be diffused to illuminate a large area. In general, the larger the spot size on the diffuser, the smoother the illumination will be on the object.

Shutter

For exposures of ½-second or longer, the most effective shutter is a piece of black cardboard. It can be used by placing it directly in front of the laser while the film is being positioned, and manually operated during the exposure. For shorter exposures, commercially available electronic shutters can be used or, if available, a focal plane shutter camera body can be used. In the later case, provisions should be made so that the shutter is mounted not on the holographic table, but directly on the table that supports the entire system.

Expendable Material

Expendable materials used for holography include film and processing chemicals. Film is advocated over plates for educational purposes because it can be cut conveniently into small pieces for testing purposes. Although emulsion ooated on glass plates is available, they are in general more expensive and cannot be cut easily.

The film used for reflection holograms must be without anti-halation backing (8E75NAH). On the other hand, transmission holograms are best made with anti-halation (8E75AH, 10E75AH, 20E75AH). If one is confined economically to purchase only one type of film, the non-anti-halation one (8E75NAH) is the choice because it can make any type of hologram.

All processing chemicals are available in photographic supply outlets with the exception of mercuric chloride, which can be purchased from chemical supply houses.

Support Facilities

Holography should be performed in an interior room which can be darkened and without excessive cross ventilation. If water is not available, exposed film can be placed inside an opaque box and carried into another room for processing. In the event that there is strong cross-current caused by the ventilation system, shrouds should be placed around the holographic table in the form of curtains with cloth or plastics. The support for this shroud can be constructed with 2 x 4's and should not touch the holographic table.

Other Supporting Equipment

The following items are desirable, but not absolutely necessary:

(1) Light meter. Gossen's "luna-pro" is most highly recommended. It has the greatest range of sensitivities, suitable with the smallest or the biggest lasers. Other light meters can be used if they can register light reflected from the object to be holographed.

(2) Green safe light. A green safe light can be fashioned by covering a desk lamp with a green gel and operated from an auto-transformer.

(3) Piece of polaroid for checking the polarization of the laser light.

(4) Two meters of nylon cord or string for measuring beam path lengths.

(5) Photographic processing trays. If these are not available, glass beakers will suffice for small holograms.

(6) Photographic prongs and film clips for holding onto the film while processing and hanging them up for drying.

(7) A photographic squeegee for fast removal of water from the processed hologram.

(8) A hair dryer for quick drying of the processed hologram.

(9) A microscope illuminator or a spot white light source for viewing reflection holograms.

(10) Rubber gloves for handling the film during processing.

Sample Shopping List

For the convenience of starting a holographic program with a minimum budget the following "shopping list" is offered. Equivalent material can be substituted if it is already available. It is true that specific mention of vendors will not permit bidding. On the other hand, those named below, to the knowledge of the author, are offering the lowest price. In several cases they are the only sources for the items described.

MINIMUM MATERIAL REQUIREMENT

ITEM	NUMBER REQUIRED	VENDOR ADDRESS	CATALOGUE #	PRICE@	TOTAL COST
Helium Neon Laser (Uniphase output)	1	Spectra-Physics 1250 West Middlefield Rd. Mountain View, CA 94040	Mod. 155	115.00	115.00
Mirror (front-surfaced), 25x35mm	2	Edmund Scientific Co. 430 Edscorp Bldg. Barrington, NJ 08007	30,286	4.75	9.50
Mirror (front-surfaced) 4" x 5"	1	"	40,042	3.00	3.00
Lens, 5mm dia., -4mm f.l.	2	"	94,440	.80	1.60
Lens, 36mm dia., -38mm f.l.	1	"	94,496	1.50	1.50
Ground glass, 4"x5"	1	"	2148	1.75	1.75
Plate glass, double-wt. 4" x 5"	3	Hardware store		.35	1.05
PVC pipe, 3" dia. x 10'	1	Plubing supplier		10.00	10.00
Holographic film, 8E75 AH 5' x 10" roll	1	Integraf P.O. Box 586 Lake Forest, IL 60045	8E75AH	30.00	30.00
Holographic film, 8E75 NAH 5' x 10"	1	"	8E75 NAH	30.00	30.00
Processing Chemicals (see Appendix I)	1 gal. each	Camera Store		-	20.00
Silica sand	200 lb.	Construction company		5.00	10.00
Wood, 1" thick, sufficient to make 3' x 4' box					15.00
			TOTAL		$248.40

Table No. 1

CHAPTER VI

Preliminary Experiments

The following preliminary experiments accomplish two major purposes. Firstly, they allow the student to familiarize himself with the system he is about to use, its tolerance to vibration and other environmental factors, the characteristic and limitation of the laser being used, and the making of the most elementary but useful type of holograms. Secondly, he is induced to perform a set of experiments that involve basic exercises physics students have been traditionally required to perform. These include the use of the Michelson interferometric technique to check the dimensional stability of, and the environmental effects on the holographic system; the measurement of the so-called coherence length of the laser by measuring the frequency difference between two adjacent frequencies emitted simultaneously by the helium neon laser (this equivalent experiment was traditionally done using the sodium D lines and a Michelson interferometer); and the making of diffraction gratings using holographic techniques. The last item allows the students to make gratings with higher resolving power than immediately obtainable from traditional ruling techniques used to produce them.

Michelson Interferometer

For convenience, let us first set up a standard set of notations for optical components used in performing our experiments and for making holograms.

	Front surface mirror		- Lens
	Beam splitter		Ground glass
	+ Lens		Pinhole
	Laser		Hologram, or film

In performing experiments in this chapter, the pinhole is optional and the ground glass will not be used.

Figure 1 shows a schematic diagram for checking the dimensional stability and the response of your system to the environment. Since the laser is the most vulnerable and usually the most expensive piece of equipment in the system, it should be handled with utmost care. It should be situated first on the system in such a way that it is unlikely to be touched in subsequent activities. In case a sandbox system is used, the laser should be set on top of a board. Never allow the beam to cross over the top of the laser because the heat waves will move it. For units that have open vents which leak incoherent light from the laser tube, covers should not be placed directly on top because it would cause overheating. But rather, a shroud should be made to direct the heat away from the table, yet shielding the light from the rest of the system. In order that a great portion of the table is tested, the distances between the beam splitter and the two mirrors should cover a greater portion of the table and should be equalized within a few millimeters. These distances can be measured with a meter stick or a string. The basic technique in obtaining an interference pattern on a screen or a piece of white paper across the room involves first placing the beam splitter (plate glass) at a 45° angle relative to the incident beam so that there will be reflected and transmitted beams making approximately 90° with

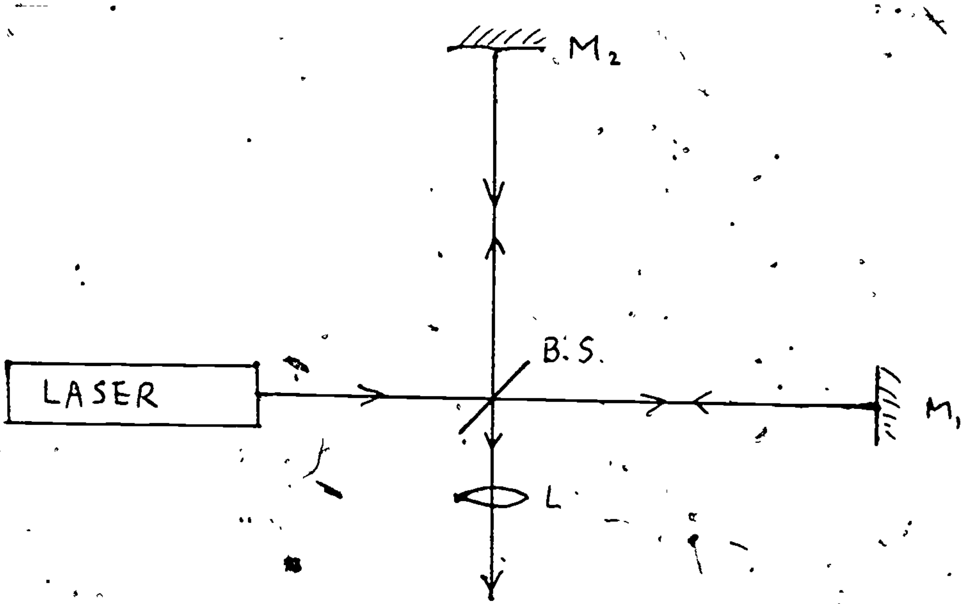

Fig. 1

each other. Next, place the two mirrors at equal distances from the beam splitter and direct them in such a way that the light returns from each mirror meeting at a common point on the beam splitter. Parts of these two beams then will meet on the screen. It will be noticed that there are more than two spots because of the two surfaces on the beam splitter. Merely ignore spots other than the brightest one from each of the two mirrors. The lens, which can be positive or negative, can then be placed at the location shown. The diffraction pattern consisting of almost straight red and black lines will appear on the screen.

One precaution that should be taken is that light from the mirrors should not be directed at the beam splitter in such a way that some will re-enter the laser. Instability in the amplitude of the laser output will result because of this feedback.

For the system to be usable for making holograms it is absolutely necessary that this interference fringe pattern observed should be stationary. If, for example, a dark line is observed to move either slowly or quickly into a location of a red line, it is equivalent to the complete destruction of a pattern being recorded on film later. For a system supported by inner tubes as suggested in a previous chapter, these fringes should be stationary. If not, look for mechanical short circuits such as having a hard object leaning against the table from the support.

By touching the table one can observe fringe movement and the time it takes for this movement to subside. This is the relaxation time of your system. Subsequently, each time you touch the table, you must wait at least through this period of time before making holographic exposures. Next, walk around the room and see if your movement induces vibration in the system. In addition, observe the effect of the movement of air you created either through your motion or the ventilation. Placing a hand under one of the beams, you can demonstrate the effect of heat waves on the fringe stability. Observe also whether or not, after the fringes have been shifted due to induced motion, they return to the same location on the screen. If they do not or if the fringes are slowly moving across the screen, never returning to their original position, it means that the system is continuously deforming. Such a system will not make holograms, or at its best will make only poor holograms. The introduction of an additional number of inner tubes underneath usually improves this condition.

Coherence Length

With the basic set-up already achieved, we now can proceed to measure the so-called coherence length or the temporal coherence of the laser. As is the case with any resonant system, such as a vibrating string or an organ pipe, the laser is naturally capable of emitting more than one frequency simultaneously. In fact, this is unavoidable for the smallest helium neon laser in the market. They typically emit two to three frequencies. The frequency difference can be calculated using the same formula developed for the vibrating string or the organ pipes,

$$\Delta f = C / 2L$$

Here Δf is the frequency difference between adjacent modes; C, the velocity of the wave involved, in our case the velocity of light; and L is the length of the cavity, which in our case is the distance between the two mirrors inside the laser. Thus, for a 50 cm laser, the frequency difference between adjacent modes is approximately 300 MHz.

For simplicity let us assume that your laser is emitting a beam consisting of two frequencies differing by 300 MHz. Each of these frequencies is making an independent interference pattern on the screen. In the event that the two mirrors are precisely equal in distance from the beam splitter, the fringe pattern on the screen will be precisely the same regardless of the frequency. However, if the paths were not equal, there will be a case of anti-coincidence where the bright line from one set of fringes is located at the dark line of the other, resulting in the complete disappearance or low contrast in the observed pattern. This, in effect, means that you may have a perfectly stable system and yet make no holograms, because, in effect, each frequency in your laser is making an independent hologram which cancels out the other one.

It is useful, then, to know how much tolerance your laser has, which ultimately determines how large an object you can use for the scene in your hologram.

The procedure for measuring this coherence length is as follows:

Begin by moving both mirrors very close to the beam splitter, but with an equal distance as measured by a meter stick, thus obtaining a high contrast set of fringes on the screen. Now move one of the two mirrors a centimeter at a time and stop to observe the fringecontrast each time. As the difference in the paths increases, the loss of contrast will become obvious. Continue to move the mirror until the contrast is maximized once again. Operationally, you can define the total path difference as the coherence length of your laser. Since the beam passes from the beam splitter to the mirror and back, the coherence length is then equal to twice the net difference in mirror distances from the beam splitter.

If lasers of various lengths are available, a useful and instructive experiment is to measure the relative coherent lengths among them and compare them to the lengths of the laser cavities. It should bear out the fact that the longer the laser, the shorter the coherence length.

We learn from this experience that in all our subsequent work in which two beams are to interfere, the distance that they travel, beginning from the beam splitter, must be equalized to optimize the fringe contrast.

Making Diffraction Gratings

We now proceed to make the simplest of all holograms - a diffraction grating. In doing so, we will be learning about exposure and processing techniques that are common to all future experiments.

Figure 6-2 shows a configuration for forming a so-called single side-band sine grating. By directing two beams separated at a 45° angle onto a holographic film, an interference pattern in the form of parallel straight lines will be formed.

Assuming that 8E75 anti-halation film is used, we begin by discussing the technique of film handling.

Since this emulsion has a sensitivity of approximately 200 erg/cm^2, which is low compared to photographic film, it allows sufficient amount of room light present without being fogged. Thus this film is suitable for lecture demonstrations where an instructor can construct holograms in full view of an audience, if proper safe lighting is used.

Assuming that no sensitive (expensive) light detectors are available, our entire procedure can be performed in the following way. Enter a completely darkened room and allow five to ten minutes for dark adaptation.

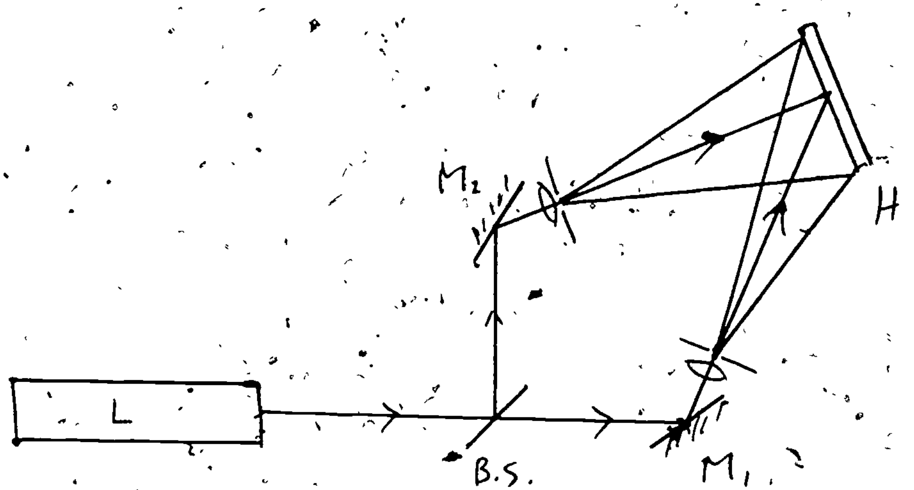

Fig. 2

Then slowly turn up the voltage on a desk lamp by having it connected to an autotransformer, and direct the light on the floor or at a distant wall. When the light level is reached so that one can barely see all that goes on and without stumbling, it is safe for handling the 8E75 emulsion. If a green gel is available, it can be used to cover the lamp. In this case, a great deal more light can be used. In case of doubt, place a piece of film on the holographic system and expose it to the ambient light for ten minutes or so and develop it as if it were a transmission hologram (Appendix I). If after the fix but before the bleach, this film is visibly darkened when viewed against a bright background, then the film has been fogged. Otherwise, it should be almost perfectly clear.

Under this condition, film can be cut and sandwiched between glass plates held together with paper clamps. Prior to its exposure the laser should be warmed up for at least ½-hour and extraneous beams reflected from the second surface of the beam splitter should be cut off by placing opaque cardboards at the desired locations. For optimum results, a 50-50 beam splitter is desirable over plate glass, although the latter will perform satisfactorily. In these as well as in all future procedures, the laser should never be turned off prior to exposure. Instead, a black cardboard should be used to cover the beam at the exit of the laser when the film is put into position.

In making the exposure, the card is lifted off the table but remains blocking the beam through a relaxation time, and then the exposure is made. This method is satisfactory for exposures ½-second and above. To determine the correct exposure, the well-known "setp-wedge" technique can be used. It can be done, for example, by making different exposures to several small pieces of film, each time doubling or halving the exposure time. After processing, the correct density and, therefore, exposure can be chosen. If a Gossen Luna-Pro meter is available, a reading of 14, when aimed at the strongest direct beam from the location of the hologram without the diffuser, indicates an exposure of one second. With this, one can extrapolate all other exposures. A reading of 13 means 2 seconds, 15 means ½-second, etc. Without the Luna-Pro but with other meters, the step-wedge test can be performed for calibration. If a neutral density scale is available, it can be used to compare with your exposure to determine what the density value of 1 appears to be. Without this scale the optimized grating can be obtained experimentally by making different exposures and observing the quality of the result by measuring the diffraction efficiency of the subsequent grating.

After the final processing and drying, a direct laser beam can be incident on the grating and a diffraction pattern would be observed on a screen. It should consist of a bright spot on one side and a dim one on the other of the directly transmitted beam. An optimized grating can result in the first order diffraction of at least one-half of the light energy.

Further experiments can be performed by constructing Gabor gratings as described in Chapter IV. This will effectively form a focusing diffraction grating and can be used to demonstrate the real and virtual image of a bright object illuminated by laser light.

CHAPTER VII

One-Beam Holograms

Once we have a system satisfying all the requirements of dimensional stability, vibration isolation, and the necessary environmental conditions, we are ready to construct various types of holograms.

We begin with the formation of a series of "one-beam" holograms - reflection, transmission, and cylindrical types - because of several reasons: (1) simplicity; (2) efficient use of light; and (3) general usefulness.

Pedagogically, it is a good philosophy to have students perform, at the very beginning, experiments that can be successfully completed in one afternoon's laboratory period. Whether or not they understand fully the theory behind what they have done, they have in their possession a hologram with which they can demonstrate to their peers, giving them a psychological boost toward learning the basic theories behind, and to continue to do more advanced experimentations.

White Light Reflection Hologram

We begin with a hologram which theoretically is among the most involved, but experimentally exceedingly simple. Essentially we shall cover an object to be holographed with a piece of film, illuminate the film with a single expanded beam of laser light, and result in a hologram which can be viewed with white light, showing a three-dimensional color image.

Figures 7-1a and b show two possible configurations. In both cases the laser beam is spread out by either a positive or a negative lens or, if available, a spatial filter. This expanding beam is directed

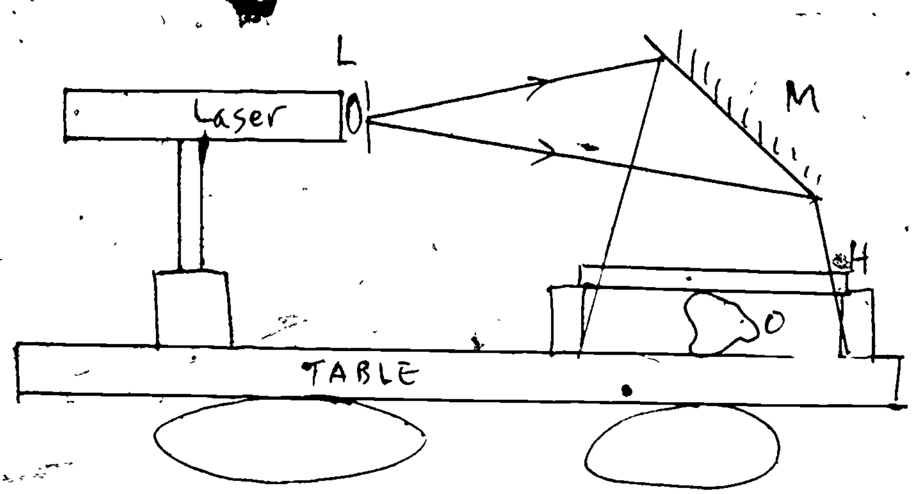

Fig. 1a

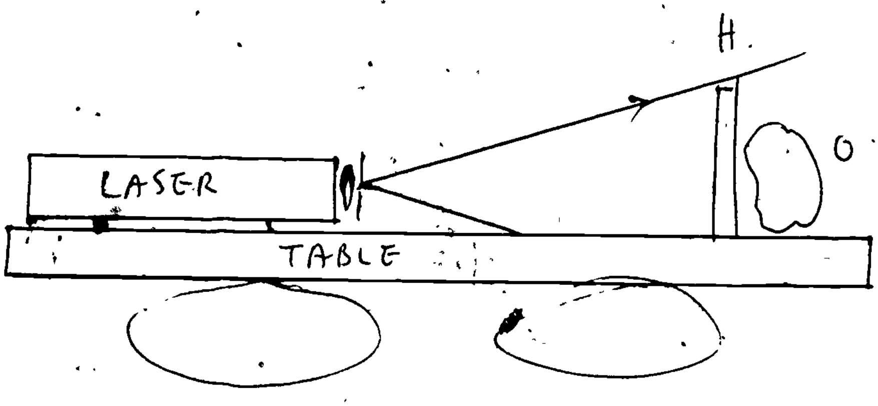

Fig. 1.b

perpendicularly onto the non-anti-halation backed (NAH) type 8E75 plate or film, which is virtually in contact with the object to be holographed. If film is used, it must be pressed between two plate glasses and held with clamps. The scenes used should be either white in color or highly reflective, shiny objects placed in virtual contact with the emulsion.

The exposure and processing can now be performed in a way similar to that discussed in a previous chapter in the construction of gratings. The length of exposure can be approximated by knowing the output of the laser, the spot size of the beam on the film, and the sensitivity of the film. For example, for a one milliwatt laser with a 5 cm diameter spot on the film which has a 200 erg/cm^2 sensitivity, the approximate exposure time is in the order of one second.

The image of this hologram cannot be seen until it is thoroughly dried and then viewed under a point source of white light, such as sunlight. Because of the emulsion shrinkage the color of the object generally will appear to be yellowish green. If one moistens the emulsion side by steaming the hologram, which can be accomplished by placing it above a cup of coffee, the image will turn red because of the swelling of the emulsion. This is a vivid demonstration of the Bragg diffraction phenomenon normally performed with X-ray. The physics involved in the formation of this hologram can be understood from the discussion in Chapter III. Here interference is caused between the direct beam incident on the emulsion and the light that has been transmitted through it and reflected back by the object. Because the film is located <u>between</u> the reference beam and the object beam where the concentration of the "mirrors" is the greatest, the 6 micron emulsion has approximately 20 mirror surfaces formed inside of it. This allows efficient Bragg diffraction to take place when illuminated by white light. The most desirable beam ratio for forming this hologram is 1, i.e., the beam intensity incident on the film from both sides should be equal. In the present case we have no control over how much object light is obtainable except by the choice of color, reflectivity, and proximity of the object to the film. Thus, the brighter the object and the closer it is to the film, the better the hologram. We can conclude that so long as we are making this type of hologram with a single beam, the depth of the scene is limited to a few centimeters.

Transmission Hologram

Figure 7-2 a and b show possible configurations for forming a one-beam transmission hologram. Here it is desirable to use anti-halation-backed (AH) holographic film with the emulsion side facing the light. In general, if film is cut from a roll, the concave side of the film is the emulsion. However, on a humid day, the emulsion may swell and curve the wrong way. The best technique to determine the correct side is to moisten one's finger and touch a corner of the film. The sticky side is the emulsion.

Here it is desirable to have the beam spread out to cover a ~~much~~ larger area than was the case with the reflection hologram. A negative lens located downstream from the spatial filter or a series of two negative lenses will achieve this effect.

In order to minimize the effect of intermodulation noise (Chapter III), a desirable ratio between the intensity of the direct light received by the film versus the reflected light onto the film by the scene is approximately 4 or greater. With a light meter which

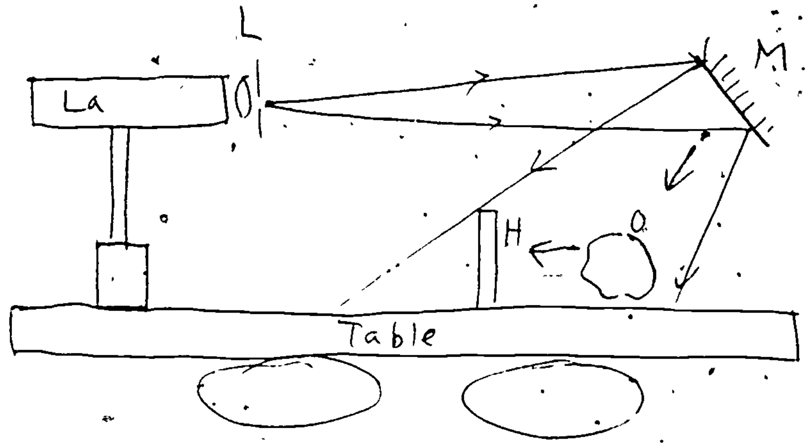

Fig. 2a

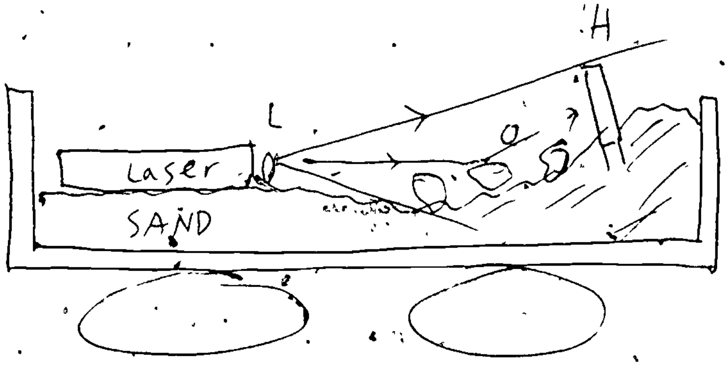

Fig 2b

has a logarithmic scale, the light as detected when aimed from the location of the hologram toward the lenses should read at least two stops higher than light arriving at the meter from the scene. In detecting the intensity of the object beam care should be taken in blocking the direct reference light from entering the meter. The exposure time is chiefly determined by the intensity of the reference beam. Exposures now can be made and the hologram processed. The resultant hologram must be viewed with a monochromatic light source, such as the laser. The real image of this hologram can be projected on a screen by shining an undiversed laser beam precisely backwards through the hologram from the original reference beam direction. A major advantage of this hologram over the reflection type is that the depth in the scene is virtually unlimited. In a sandbox, for example, one could have a broad desert scene in front of the film if the laser light is spread out sufficiently.

One limitation of this hologram is that most of the scene is backlit. A primary caution is not to have objects so tall as to block the reference beam.

An easy variation in this hologram is to record more than one scene on the same hologram. This can be done by making two separate exposures on two scenes. For example, after making one exposure the film can be turned 90° along the axis perpendicular to the film plane. A different scene is substituted and a second exposure made. In this case the exposure of each scene should be one-half of the original exposure for a one-scene hologram. After processing, the hologram can be rotated, and two different scenes will be viewed depending on the orientation.

Cylindrical Hologram

Figure 7-3 shows a configuration for making a cylindrical hologram in which objects recorded can be viewed all around. The cylinder used for supporting the film can be anything from an olive jar to a section of pipe. As a start, use a cylinder approximately 5 cm in height and 8 to 10 cm in diameter.

The mounting of the film onto the inside of the cylinder is crucial. Having cut it to the precise dimensions that can fit inside the jar, the film should be held inside with the emulsion side inward, and taped onto the cylinder with all portions of the film in physical contact with the cylinder wall. The cylinder then should be left on top of the holographic system for several minutes to allow it to reach thermal equilibrium.

As shown in Figure 7-3, two laboratory stands are used on top of the vibration isolated system. With larger lasers a mirror should be used on top of the stand to reflect light downwards from the laser positioned on the table. This is followed by one or two beam-expanding lenses so that the light is diverged in the most extreme fashion feasible. In this as well as in all other cases, care should be taken so that the edges of the lenses must not be illuminated.

To assure that the illumination of the cylinder is evenly distributed, a white piece of paper cut to the size of the film and mounted inside the cylinder can be used for visual observation. A light meter can be used to check the scattered light from the paper all around the cylinder, and the beam moved by the lenses to achieve the most uniform possible illumination. The object to be holographed can now be placed

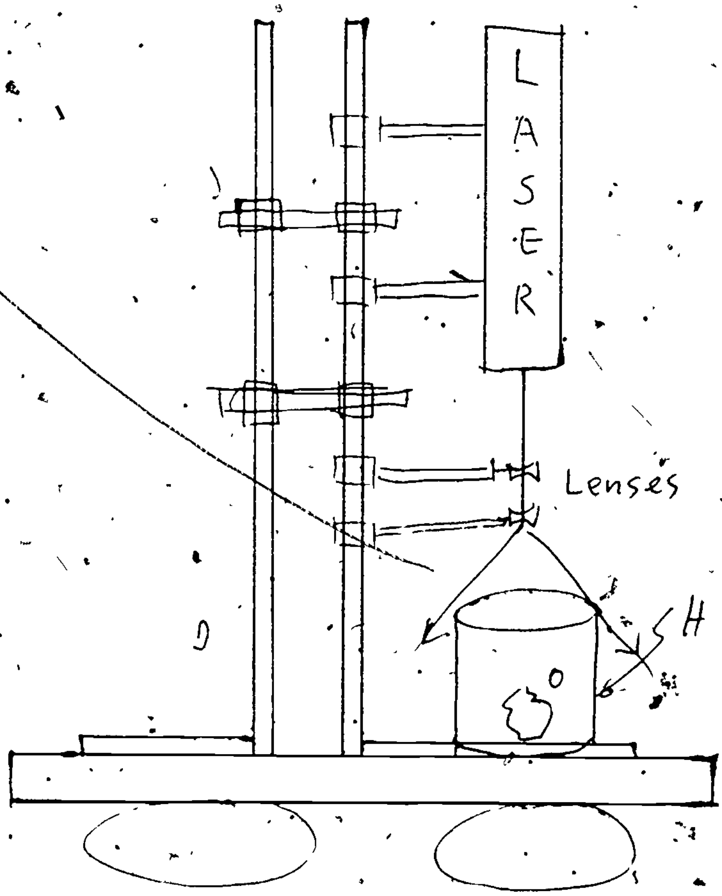

Fig. 3

at the bottom of the cylinder. Again, highly reflective objects are preferred over dark ones. The beam ratio can be checked as before. Since this is a transmission hologram, the intensity ratio of four to one is desirable. In the event that this is far off, corrections can be made by moving the expanding lenses farther up or down to change the divergence of the light.

For a simple system using a single laboratory stand, wobbling will cause sufficient motion to destroy the hologram. A second laboratory stand is necessary to dampen this vibration by tying it with right-angle clamps and rods to our system.

The exposure and processing procedures for this hologram are precisely similar to those for the transmission hologram. Again, a second scene can be recorded on the same film if the cylinder is inverted, and a second scene exposed.

CHAPTER VIII

General Multiple Beam Hologram Formation

Having familiarized ourselves with the basic laboratory procedures stated in the previous chapter, we now outline some general techniques for hologram formation involving the use of multiple beams. The material requirement is necessarily increased, particularly with regard to the number of mirror, lenses, spatial filters, and beam splitters.

In Chapter VII, holograms are formed between the direct light arriving at the film with the light scattered from the object. In these cases no beam splitters were used. Because of the simplicity involved it was, comparatively speaking, difficult to arrange the desirable beam ratio and, in general, impossible to equalize the paths of the two beams. Moreover, we also had to accept whatever state of polarization existed, and were unable to control this factor. On the other hand, because of the minimum number of components used, lasers with minimal output were usable.

In general, as we introduce more and more control to our system, there will be greater waste of laser output. For practical purposes, if multiple beams are to be used in hologram formations, it is highly desirable that lasers with outputs greater than 2 mW be available.

Figure 8-1 shows one of many possible configurations for forming two-beam holograms. Beginning with the laser, the beam is directed to the right by mirror M_1 and is then split into two by the beam splitter. With a white cardboard acting as a screen at the location of the future hologram, the reference beam can now be aligned by M_2. The object to be used can be now located in front of the screen, and is illuminated with the object beam directed on it by M_3.

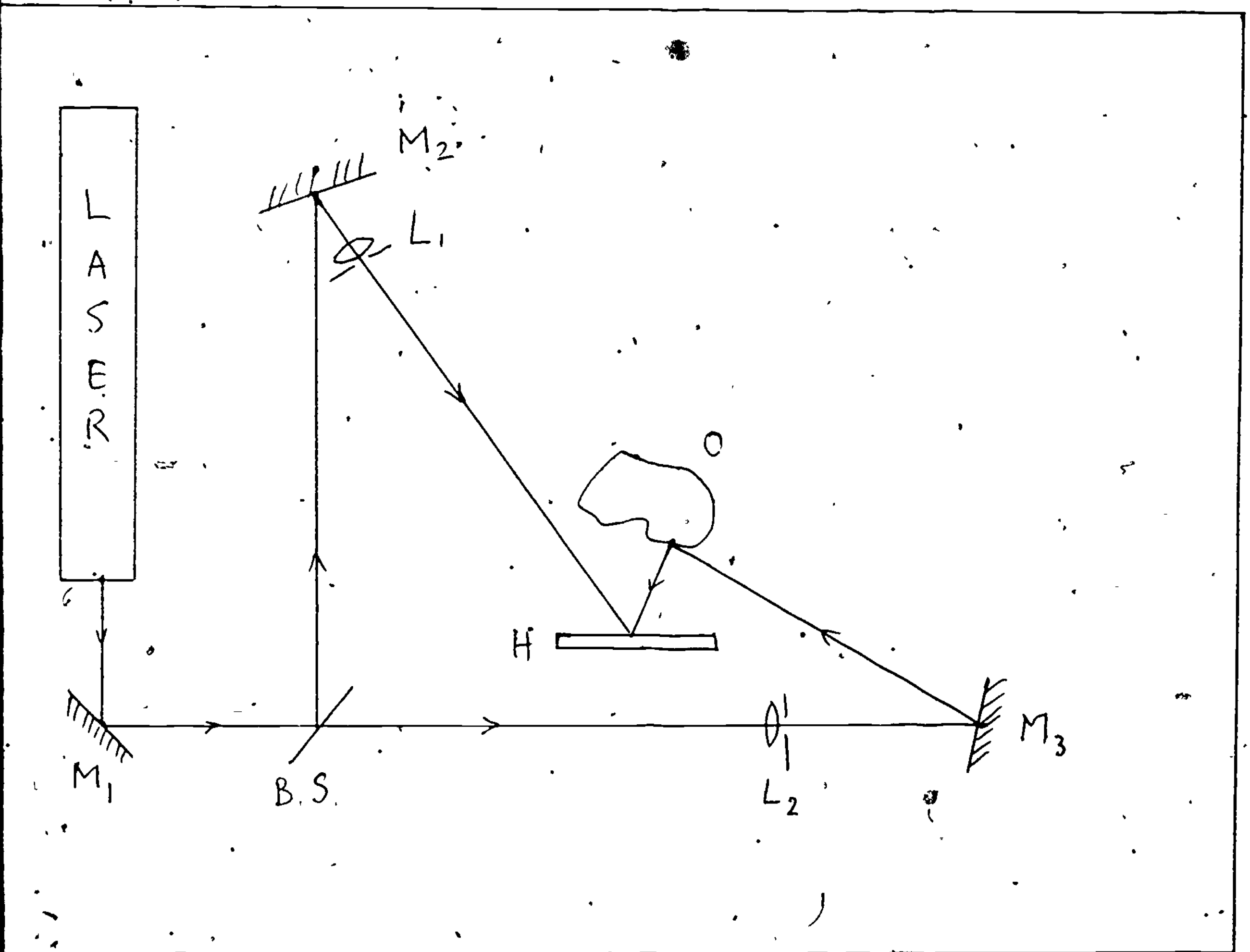

Fig. 1

Before spreading out either beam, the optical paths can now be approximately equalized by the adjustment of M_2 and M_3, so that $\overline{B.S.M_2H} = \overline{B.S.M_3OH}$.

A lens L_1 can now be introduced to expand the reference beam. Similarly L_2 expands the object beam to illuminate the object uniformly. It is important to note here that whereas the reference beam must always be a point source, the object, on the other hand, can be diffusely illuminated. Figure 8-2 illustrates this alternative. In this case the object beam is first expanded, then a ground glass is used to diffuse the light that illuminates the object. Care should be taken that none of the light scattered from the ground glass arrives at the hologram directly.

The beam ratio can be measured by blocking one beam at a time. The intensity of each can be checked with a light meter. As stated before, the intensity ratio between the reference and the object beams should be approximately four to one. This is not, however, a hard and fast rule because many factors are involved, the most important of which is the bandwidth.

Figure 8-3 illustrates our concept of bandwidth. Here the minimum angle between the object and the reference beam approaches zero whereas the maximum angle is approximately 90°. Thus the spatial frequency range lies between 0 < spatial frequency range < $\frac{\text{sine } 90^{\circ}}{\lambda}$. This is an example of a wideband hologram. Figure 8-4, on the other hand, illustrates the narrow bandwidth configuration. Here the spatial frequency range is obviously very small. Since the intermodulation noise is directly related to the bandwidth, and the function of the beam ratio is to minimize this noise, the beam ratio then is proportional

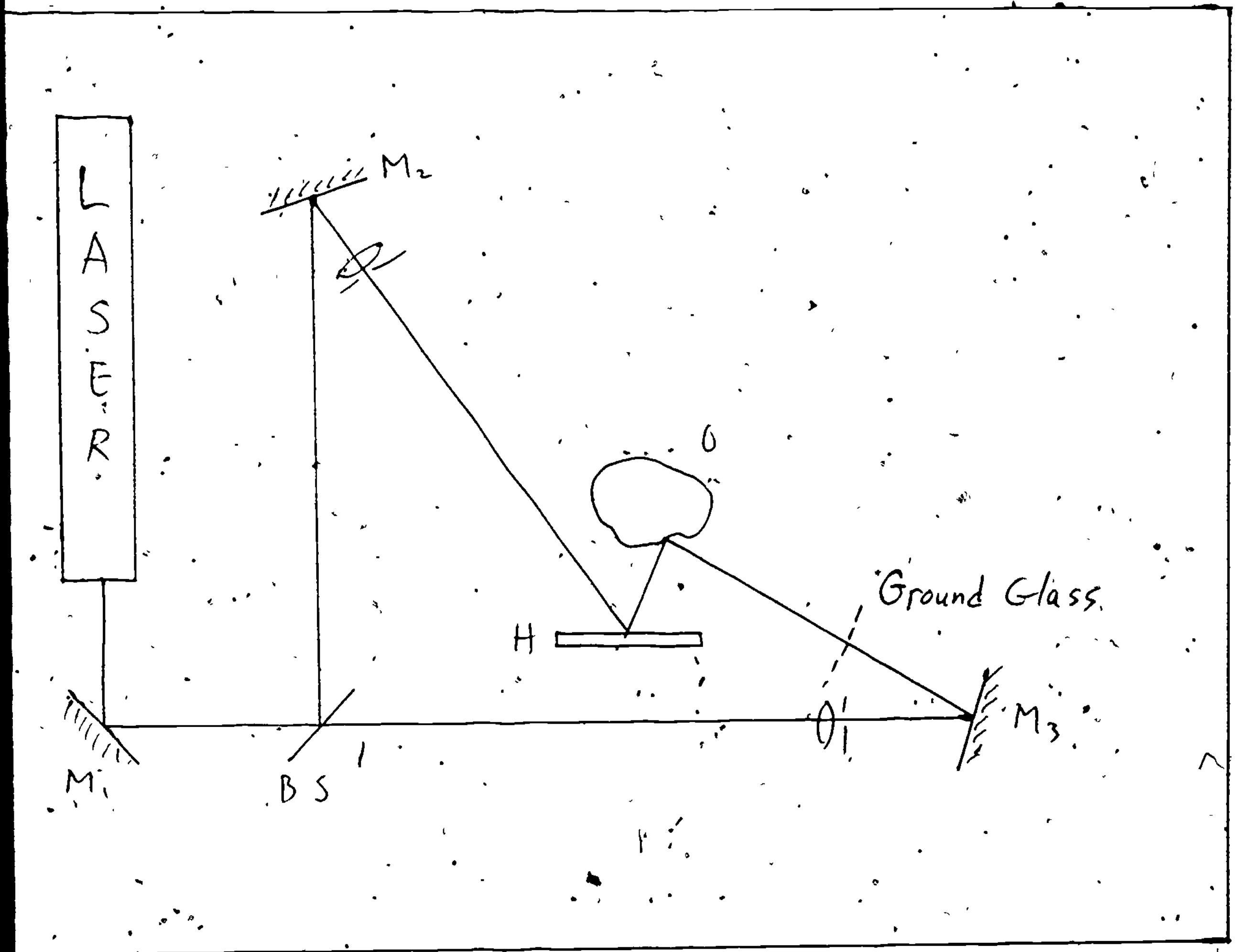

Fig. 2

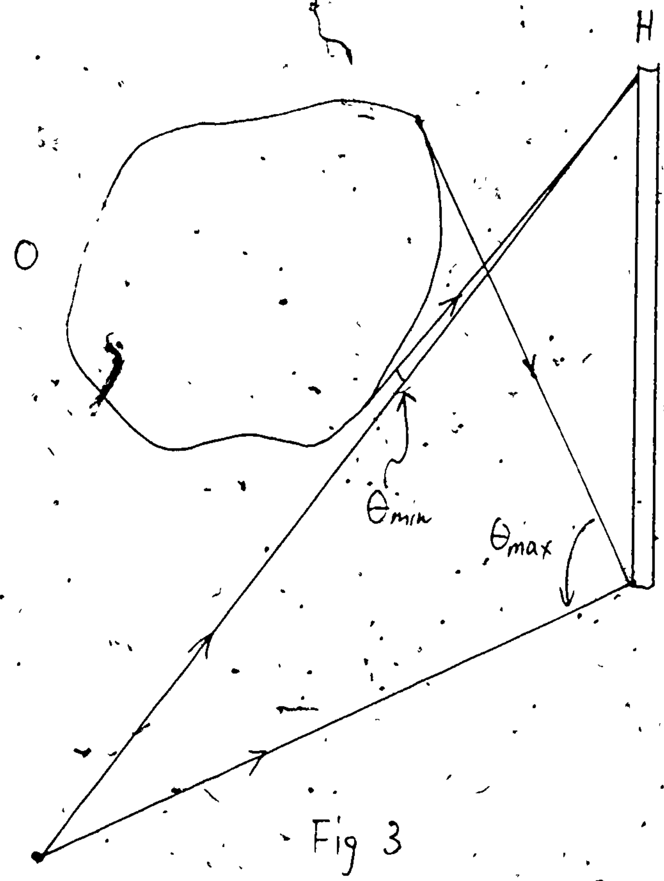

Fig 3

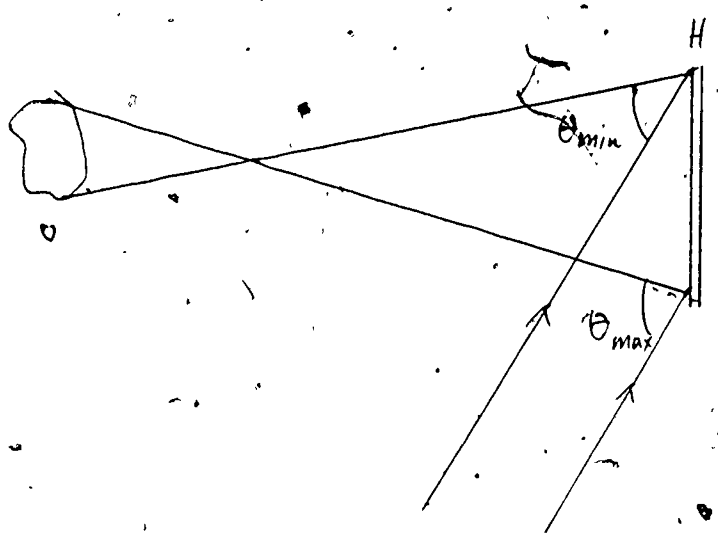

Fig 4

to the bandwidth. Thus in the formation of a sine grating where the bandwidth is zero, the preferred beam ratio is one. On the other hand, if an extremely wide scene is used, the beam ratio as high as ten to one is desirable.

Assuming a low cost beam splitter is used, which results in fixed beam ratio, this ratio can be altered by several techniques. The simplest one is to move L_1 to various locations. The further it is upstream the more light will spread out before its arrival at the hologram, thus decreasing the reference beam density. Similarly the object beam can be changed by varying the location of L_2. Another technique is to use neutral density filters. However, this wastes otherwise useful light.

In general, L_1 should be sufficiently far from the hologram so that the light covers an area greater than the size of the hologram. Because the output from a laser has a Gaussian distribution, the center of the spot has higher intensity than the edge. If the spot is smaller than the film, the center will be overexposed and the edge will be underexposed.

The next step is to determine the exposure time. Since the reference beam usually dominates, it alone determines the exposure. If a calibrated meter is not available, the step wedge method mentioned before can be used.

Following are summarizing steps for making a two-beam hologram, assuming that we have various components arranged approximately as in Figure 8-1 on top of a vibration-isolated table:

(1) Equalize the beam paths.

(2) Spread beams with L_1 and L_2.

(3) Adjust beam ratio.

(4) Determine exposure.

The hologram now can be exposed and processed.

In the event that it is desirable to illuminate the object from more than one direction, Figure 8-5 shows how the configuration in Figure 8-1 can be modified to accomplish it.

For two-beam white light reflection holograms, Figure 8-6 shows a possible arrangement. Note that the beam ratio for white light holograms should be 1, regardless of objects used and bandwidth. In this case, the intermodulation noise will appear in the transmitted beam only, leaving the reflected beam unaffected. For optimum resolution on the reconstructed image, the object should be as close to the film plane as possible.

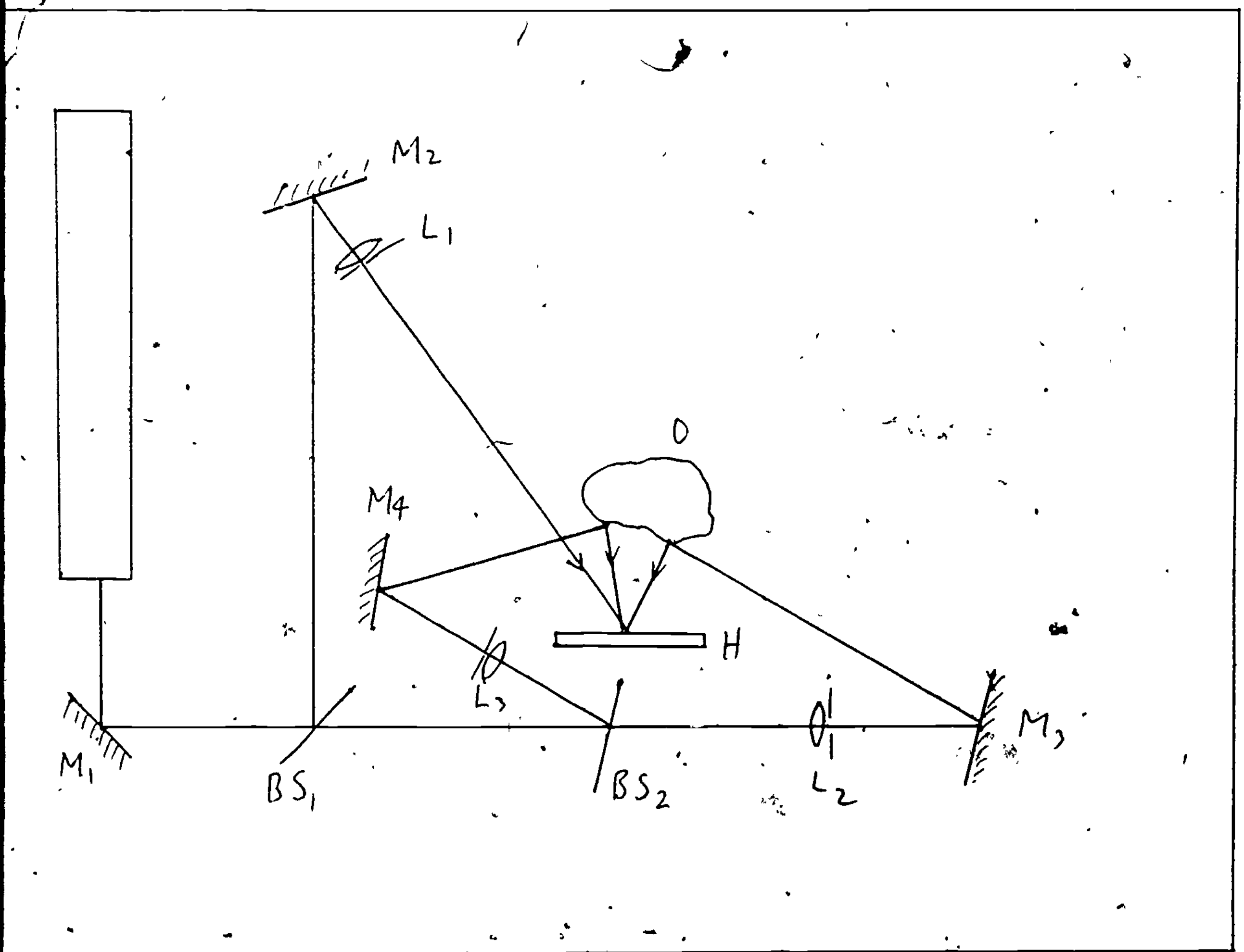

Fig. 5

CHAPTER IX

Basic Projects

Like photography, holography has both scientific as well as artistic applications. Only the ability and the imagination of the practician can limit the possibilities in both domains.

Instead of cataloging all possibilities, the format of this writing requires that we point out only the highlights and the basic techniques in holographic interferometry, which allows the students to make microscopic measurements on displacements, and some methods in image manipulation which widens the range in artistic applications.

Holometry

Holometry (holographic interferometry), as discussed in Chapter III, can be divided into three classes: double exposure, time average, and real time. We shall discuss only the first case which involves exposing a hologram to an object once, allow the object to change microscopically, and then make a second exposure. In the second case, only one exposure is made while the object is under steady-state vibration. The nodal areas that did not vibrate will be seen as bright, whereas the anti-nodal areas, where the object shifted, will appear dark. Finally, real time interferometry involves exposing a hologram and viewing it in its original location, so that both the image and the real object are superposed in space. If the object now shifts, dark fringes will be seen through the hologram. They are caused by the differences between the location of every point on the object during exposure and its present locations.

We shall now discuss the simplest case of the three, namely, double exposure. For objects smaller than the photoplate or film and with depth limited to a few centimeters, an exceedingly simple method can be used with self-calibrating interference fringes. Figure 9-1 shows a configuration for a student experiment involving the bending beam or the deformation of a membrane. Locate the photoplate directly above but not touching the bending beam. Let this beam be supported as shown, and a weight placed in its middle. A single beam white light hologram is exposed. Without moving anything else, the weight is removed with a tweezer very carefully and a second exposure is made. Upon processing this single-beam white light hologram, interference fringes will be seen on top of the beam. By having the laser light impinge on the photoplate perpendicularly, we can interpret that the first dark fringe adjacent to the point of support represents a net optical path shift of one-half wavelength or, therefore, a net displacement of one-quarter wavelength. The next dark fringe, then, represents a net displacement of three-quarter wavelength, and so forth. Thus, the fringes are directly calibrated to the wavelength of the laser used. This experimental data can then be compared with theoretical predications, making this an interesting and instructive exercise. The student is encouraged to discover other projects that can benefit from this technique. The basic precaution here is that stability for the film plate relative to the table must be insured, and that no other displacements than the one under study should be induced. In the event that dark fringes are noticeable in the vicinity of the hologram itself, this means that the hologram has moved during exposure.

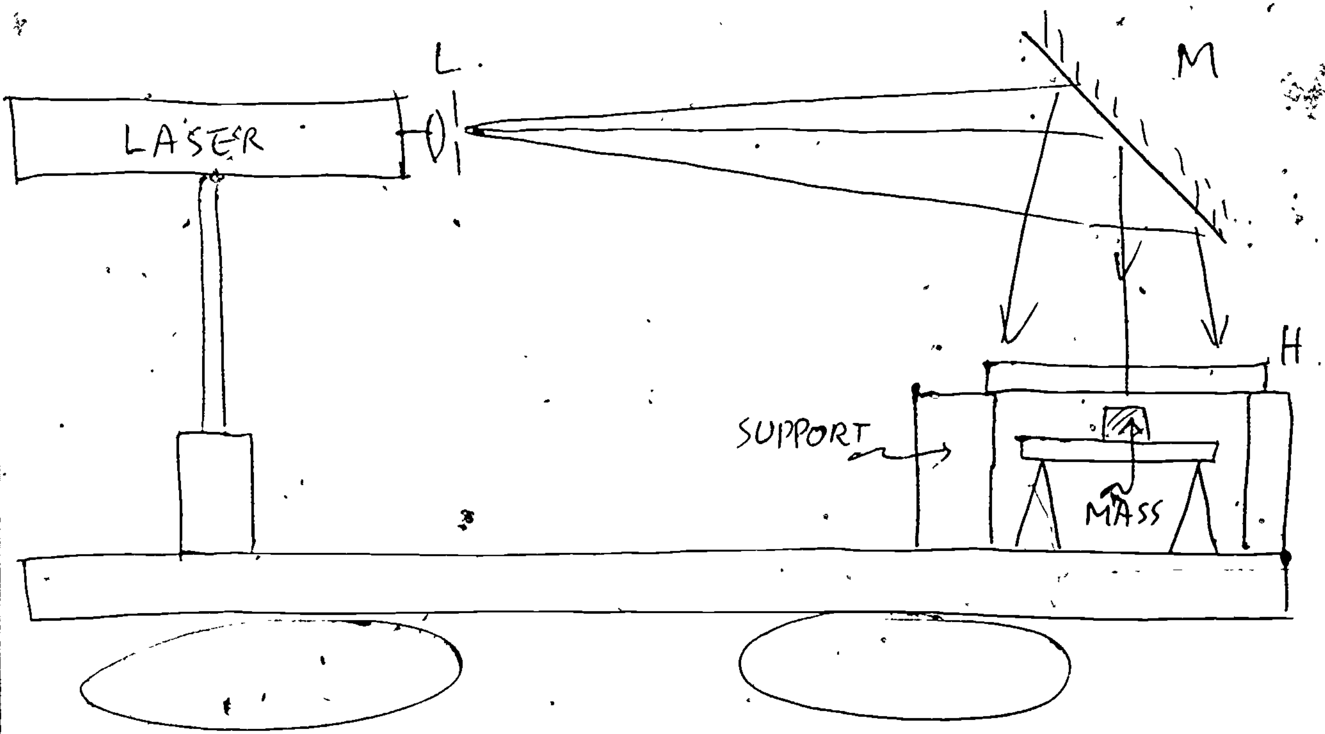

Fig. 1

In general, when objects are larger than the plate and with dimensions greater than suitable for the above simple technique, a general two-beam technique transmission hologram should be used. Under this circumstance beam paths are extremely complicated, particularly when a ground glass is used to provide diffused illumination for the object. Although the fringe structure provides much qualitative information concerning the state of deformation or shift in the object, numerical interpretation becomes exceedingly difficult. However, there is still a simple technique to self-calibrate the interference pattern. We shall call this the self-referenced fringe technique (SRF).

The SRF technique requires that the maximum displacement be known and a well-defined zero displacement point be located. For example, in the case of the bending beam the point of support provides well-known positions for zero displacement. At the location of the weight a micrometer can be provided so that the maximum displacement is known. Regardless of beam directions and configurations for forming this hologram, the interference fringes formed on the object are self-calibrated. We can divide the total displacement S indicated on the micrometer by the total number of dark fringes N between the point of support to the point of contact of the micrometer. Each successive fringe from the point of support thus represents a displacement of S/N. After the calibration an arbitrary mass can be used to displace the beam, assuming no change in the configuration for forming the hologram is made. In general it is interesting and instructive to make holograms with various displacements in various directions induced by a micrometer. This helps the experimenter to learn to interpret fringe structures by their orientations, shapes and locations qualitatively so that when he views a particular interference pattern, he immediately gets a general idea concerning the nature of the displacement.

Hybrid Holograms

In order to increase the versatility of the hologram for both scientific and artistic purposes, we shall discuss some variations from the basic techniques which will allow us (1) to view the virtual image at any arbitrary location relative to the hologram and (2) allow us to illuminate transmission holograms with tungsten filament light sources.

All holograms discussed so far have virtual images seen behind the hologram plate. However, it is possible to locate this image on the plane or even in front by a relatively simple variation of the techniques already discussed.

To make a "focused-image" hologram, a convenient method is to use a photographic lens and focus the object on the film so that, alone, a photograph would be exposed. With the addition of a reference beam either from the same side or the opposite side of the film, a transmission or reflection hologram can be exposed, respectively. When viewing this hologram, the image will appear to be straddling the plane of the film, with part of it protruding into the front and the remainder behind.

Another variation of the focused image hologram is to obtain the real image from an existing hologram and make a hologram of it. Figure 9-2a shows the usual configuration for forming hologram H_1.

If we use this finished hologram as a master and project its real image back to the location of the original object by converging a beam and focusing it through the hologram at the location of the original reference beam, as shown in Figure 9-2b, a fresh holographic plate can now be located at the location of the image. Using a converging reference beam for hologram H_2, a secondary hologram is thus formed. When it is illuminated by a point source as shown in Figure 9-2c, an image will be seen straddling the plane of the hologram. If the scene is shallow, not exceeding a centimeter or so on either side of the film, its image can be seen with white light. However, the image further away from the film will have color dispersion.

To make it feasible for illumination of this focused image hologram with deep scenes using a point source of white light, Figure 9-3 shows a variation on the previous configuration. Here we also use a master hologram, H_1, and make a secondary hologram precisely as in Figure 9-2b. However, a mask with a slit opening is placed on H_1 so that only the slice of hologram underneath the slit is used. This is equivalent to sacrificing the vertical parallax on H_1 but retaining the horizontal parallax. Illuminating the H_2 with a laser source as shown in Figure 9-4 will allow an image to be seen only if the viewer's eyes were at the location of the original slit. Moving his head up or down will cause the disappearance of the image. On the other hand, if the hologram is viewed with a white light source as shown in Figure 9-5, an entire image is seen over large range of space due to the fact that different color from the white light will cause the virtual slot to be located at a different position; so that depending on the altitude of the eyes, there will be a color changing from red

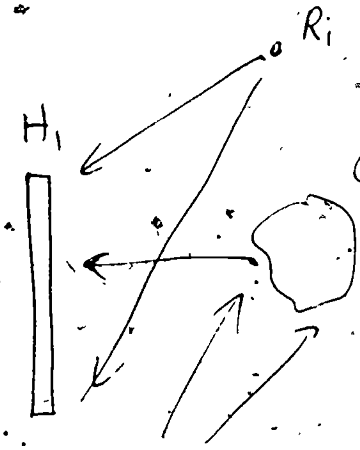

Fig. 2a

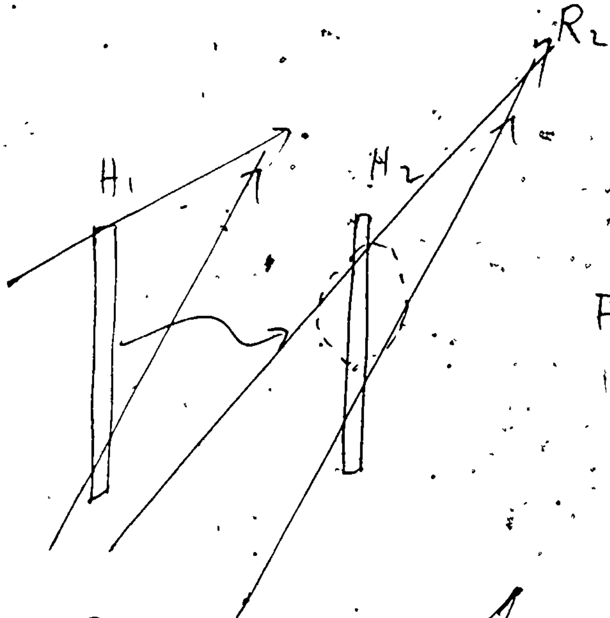

Fig. 2b

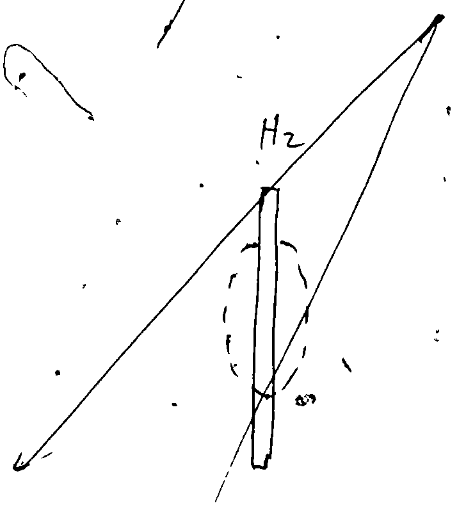

Fig. 2c

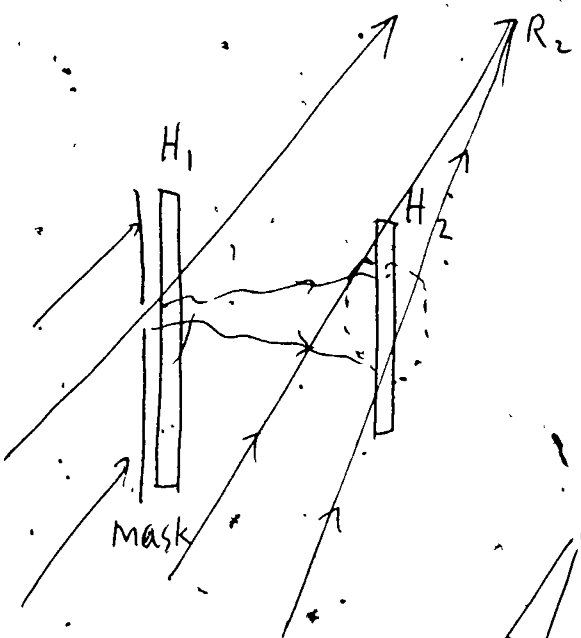

Fig. 3

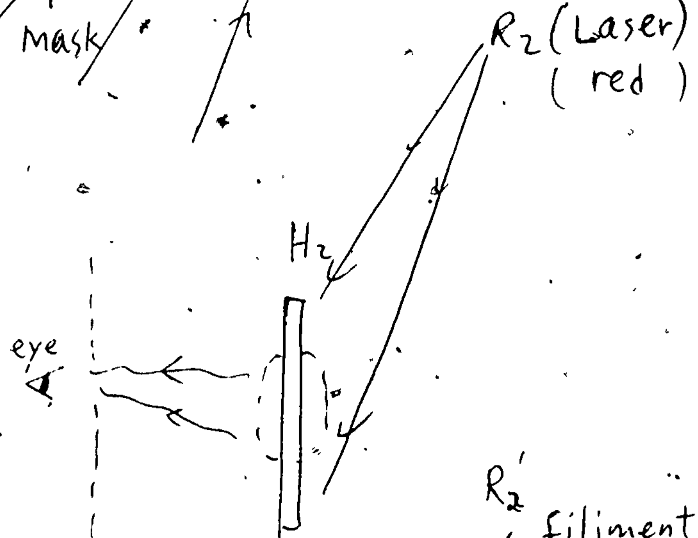

Fig. 4

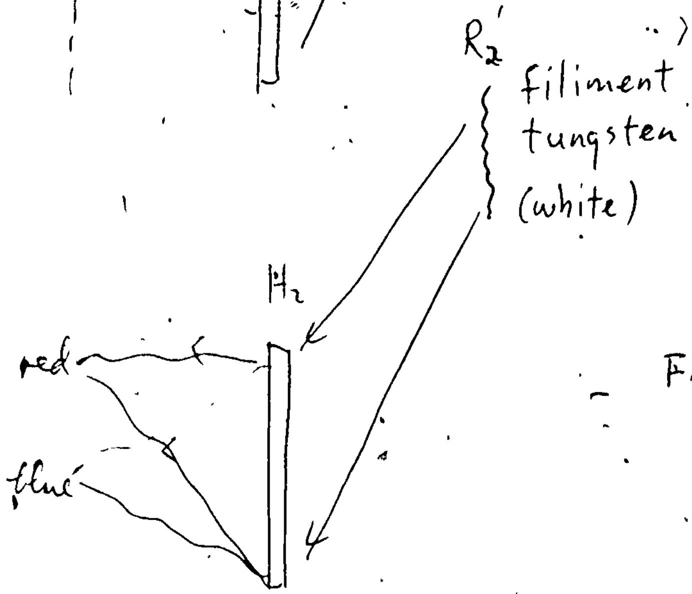

Fig. 5

"Rainbow Hologram"

to blue as one moves them up and down. But in all positions the image will be seen with perfect horizontal parallax. H_2 is now known as a "rainbow hologram". Its chief advantage is that holograms no longer require monochromatic illumination, making this much more economical to display.

There are many other types of hybrid holograms which space here will not allow us to delve in detail. Appendix III shows one technique used to integrate motion pictures into holograms so that objects originally illuminated by incoherent light are converted into holograms with motion. Further developments involve the combination of the rainbow effect with the integraphic technique, resulting in cylindrical holograms that contain objects in motion and are illuminated by commonly available tungsten filament light bulbs.

CHAPTER X

Bibliography

The peculiar nature of our subject matter demands a unique form of bibliography. Unlike a topic in sociology, where references must be carefully chosen among myriad sources, holography is a comparatively narrow subject matter which is described in a well delineated set of publications.

The background information needed for a beginning student can be found in the optics section of any introductory physics text. Whenever a technical term is encountered, such as "interference", "polarization", "focal length", etc., the student is urged to consult the index of these texts, and then learn what is necessary from them. Texts that we specifically recommend are:

PHYSICS, Robert Resnick and David Halliday, John Wiley & Sons, Inc.

ELEMENTARY GENERAL PHYSICS, Richard T. Weidner and Robert L. Sells, Allyn and Bacon, Inc.

UNIVERSITY PHYSICS, F. W. Sears and M. W. Zemansky, Addison-Wesley.

In general, any text with a good optics section will be helpful.

At a more advanced level, we recommend:

FUNDAMENTALS OF OPTICS, Francis A. Jenkins and Harvey E. White, McGraw-Hill Book Company, Inc.

OPTICS, Eugene Hecht and Alfred Zajac, Addison-Wesley (1974)

Following is a list of books written specifically on the subject of holography, listed in the chronological order of their publication:

INTRODUCTION TO COHERENT OPTICS AND HOLOGRAPHY, G. W. Stroke, Academic Press, 1st Edition, 1965; 2nd Edition, 1969.

THEORY AND APPLICATIONS OF HOLOGRAPHY, J. B. DeVelis and G. O. Reynolds, Addison-Wesley, 1967.

INTRODUCTION TO FOURIER OPTICS, J. W. Goodman, McGraw-Hill, 1968.

PRINCIPLES OF HOLOGRAPHY, H. M. Smith, Wiley Inter-Science, 1969.

THE APPLICATIONS OF HOLOGRAPHY, H. J. Caulfield and S. Lu, Wiley Inter-Science, 1970.

OPTICAL HOLOGRAPHY, R. J. Collier, C. B. Burckhardt, and L. H. Lin, Academic Press, 1971.

HOLOGRAPHIE, M. Francon, Springer Verlag, 1972.

OPTICAL AND ACOUSTICAL HOLOGRAPHY, E. Carmatini, Plenum Press, 1972.

OPTICAL INFORMATION PROCESSING AND HOLOGRAPHY, W. T. Cathey, Wiley-Interscience, 1974.

The most up-to-date one is by Cathey. This book can very well serve as our text. Most of the theory needed to increase the depth of our understanding is found here. OPTICAL HOLOGRAPHY by Collier et al. is more substantial and contains more detail on holographic materials other than silver halide emulsion. Goodman's INTRODUCTION TO FOURIER OPTICS is best on a graduate level. It offers the most general discussion on the Fourier description of optical systems, including holography.

Any of the above-mentioned texts has extensive lists of references to original publications in journals. The student should be encouraged to use the library resources and consult the articles of his or her interest.

APPENDIX I

GENERAL HOLOGRAM PROCESSING PROCEDURE*
FOR TRANSMISSION HOLOGRAMS AND WHITE LIGHT REFLECTION HOLOGRAMS

1.	Develop in D-19 (Kodak)	5 minutes
2.	Stop bath (any brand)	30 seconds
3.	Kodak rapid fix with hardener	3 minutes
4.	Wash in running water	10 minutes

All above steps should be performed at room temperature (approximately 23°C) with indirect and dim green safe light. The hologram can now be handled in full room light. If exposed correctly, it should appear dark gray, but not opaque. (Approximately 10% transmission of white light is best.) It can also be viewed with the reference beam alone. Avoid allowing it to dry at this point.

Bleaching Techniques to Achieve Maximum Efficiency

I. Transmission Holograms: (8E75 AH, 10E75 AH, or 20E75 AH film or plate) For best holograms, film with anti-halo backing should be used. Film without AH will do, but will have some unwanted patterns.

5. After step (4) above, submerge in following bleach until the entire hologram appears transparent.

   The bleach consists of 1 liter of de-ionized water with 30 grams of potassium ferricyanide and 30 grams of potassium bromide completely dissolved in it. It is toxic, extremely caustic, but not volatile. Should be kept in plastic or glass container and handled with rubber gloves.

6. Wash in running water — 5 minutes
7. Squeegee the emulsion side with a good photographic grade squeegee and then dry with warm air (hair dryer).

II. White Light Reflection Holograms: Must be made with 8E75 NAH holographic film.

5. After step (4) above, submerge in following bleach until all the gray color disappears.

   The bleach is EXTREMELY TOXIC AND CAUSTIC, but not volatile. Handle with extreme care, using rubber gloves and glass or plastic containers. It consists of 20 grams of mercuric chloride and 20 grams of potassium bromide dissolved in 1 liter of de-ionized water.

6. Wash in running water — 5 minutes
7. Kodak rapid fix with hardener until all the pinkish white color turns brown.
8. Wash in running water — 5 minutes
9. Squeegee and dry.

* The developer, stop bath and the fix can be purchased from any camera store. The bleaching chemicals can be "borrowed" from your Chemistry Department or purchased from Sargent-Welch Science Company, 7300 N. Linder Avenue, Skokie, Illinois 60076.

APPENDIX II

PHOTOGRAPHIC MATERIALS FOR HOLOGRAPHY

1. Introduction

Photographic materials for holography must meet specific requirements. Since the dimensions of the structure of the interference pattern to be recorded are usually of the order of magnitude of the wavelength of the light used for exposure, a very high resolving power is essential. A high speed is also desirable to allow short exposures.

However, high resolving power and high speed are somewhat incompatible properties, which makes it necessary to arrive at a compromise of the highest possible efficiency. The nature of the subject will determine whether the ideal solution of this problem will be slanted towards high speed or high resolving power. Agfa-Gevaert has therefore introduced a number of Scientia emulsions to meet various practical demands, namely 8 E 75 and 10 E 75 for red laser light, and 8 E 56 and 10 E 56 for blue and green laser light. We shall now discuss the specific properties of these materials.

2. Density and amplitude transmission curves

The relation between density D and exposure E is usually represented by the characteristic curve. Figs 1 and 2 show these curves for Scientia emulsions 8 E 75 and 10 E 75 for red laser light, and 8 E 56 and 10 E 56 for blue and green laser light respectively.

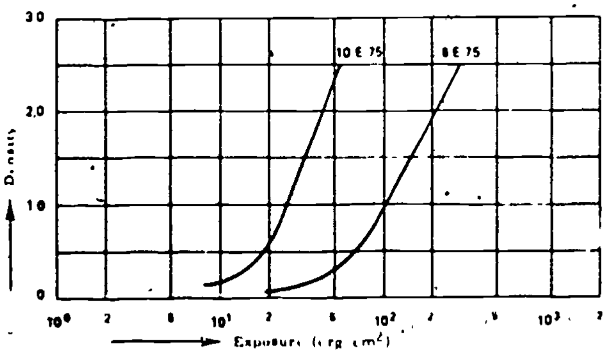

Fig Characteristic curves of Scientia 8 E 75 and 10 E 75 at 633 nm

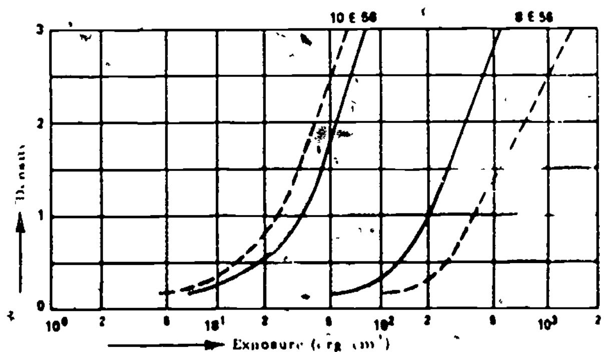

Fig Characteristic curves of Scientia 8 E 56 and 10 E 56 at 476 nm ------- and 521 nm ———

The exposures of Scientia 8 E 75 and 10 E 75 were effected at the principal wavelength of the He-Ne laser (633 nm) and those of Scientia 8 E 56 and 10 E 56 with a krypton laser (476 and 521 nm), see Figs 1 and 2 respectively. The material was processed for 5 minutes in Agfa-Gevaert developer G 3 p at 20°C and for 4 minutes in Agfa-Gevaert fixer G 334, followed by washing for 15 minutes. The density of the developed emulsion layers was measured by parallel light. Characteristic curves contain useful information in the case of certain holographic exposures, but in general amplitude transmission curves are preferred, because a hologram acts as a diffraction screen to the incident wave front, where not the local density but the local amplitude transmission is the more important consideration. Amplitude transmission is defined as the ratio between the amplitudes of a monochromatic plane wave after and before passing through the photographic emulsion. This is usually a complex quantity, in other words, not only the amplitude but also the phase of the incident radiation is affected. However, in the case of processed emulsions, for measuring amplitude transmission $|T_a|$ the only easily measured quantity is intensity transmission $T_i = T_a T_a^*$, where T_a^* represents the complex conjugate of T_a. This quantity is expressed as a function of the exposure of Scientia 8 E 75 and 10 E 75 at a wavelength of 633 nm, and of Scientia 8 E 56 and 10 E 56 at wavelengths of 476 and 521 nm respectively, in Figs 3 and 4.

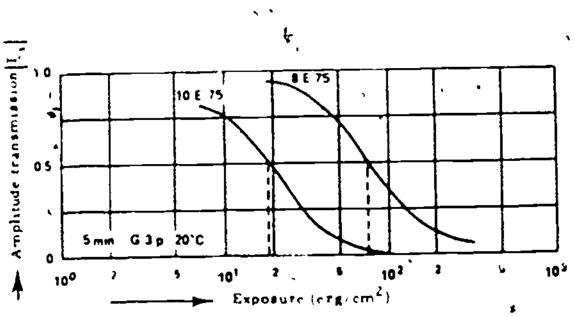

Fig 3 Amplitude transmission curves at 633 nm

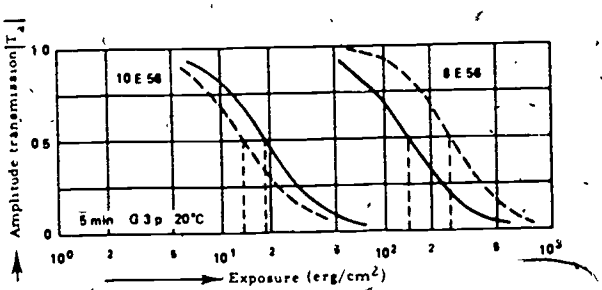

Fig 4 Amplitude transmission curves at 476 nm ------ and 521 nm ———

The energy per unit surface that corresponds to $|T_a| = 0.5$ can be regarded as an indication of the sensitivity.

Approximate values of light intensities for $|T_a| = 0.5$ (corresponding to D = 0.6) are

20 erg/cm² for Scientia emulsion 10 E 75-
75 erg/cm² for Scientia emulsion 8 E 75

at 633 nm

10-20 erg/cm² for Scientia emulsion 10 E 56
150-300 erg/cm² for Scientia emulsion 8 E 56

at 476 and 521 nm

The above values are slightly affected by development conditions.

3. Colour sensitivity

Scientia holographic emulsions 8 E 75 and 10 E 75 are specially sensitized for wavelengths between 600 and 750 nm, and are intended for use with the He-Ne laser (633 nm) and the ruby laser (694 nm). On the other hand, Scientia holographic emulsions 8 E 56 and 10 E 56 are suitable for exposure to wavelengths up to 560 nm (krypton and argon lasers). The density and amplitude transmission curves given in Section 2 apply to the wavelength of the He-Ne laser of 633 nm (see Figs 1 and 3) and those of the krypton laser of 476 and 521 nm (see Figs 2 and 4). To enable one to convert the exposure to other wavelengths, the colour sensitivities are shown in Fig. 5.

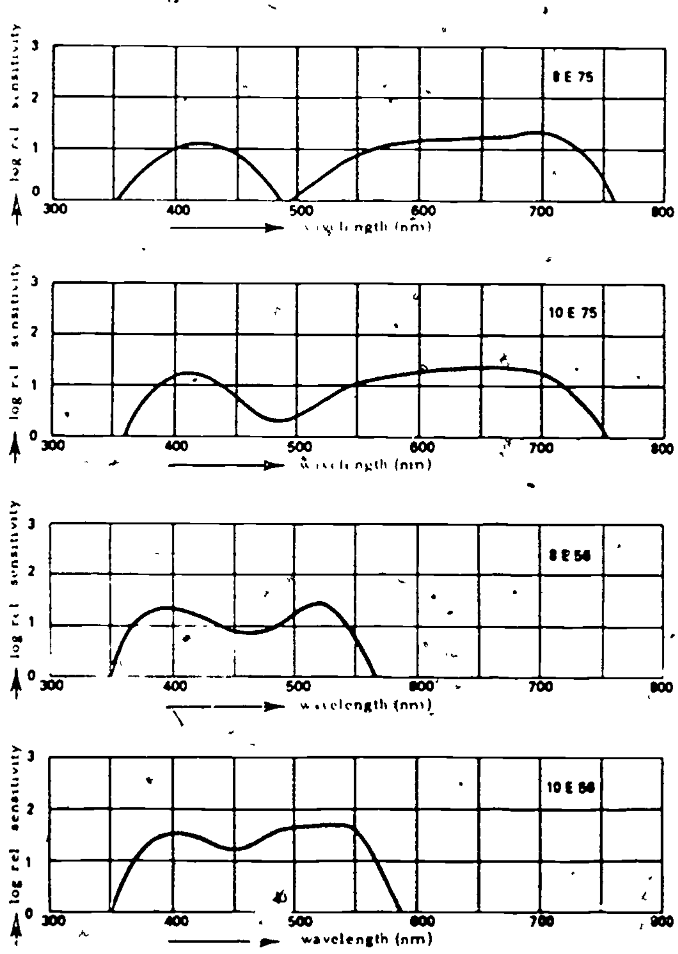

Fig 5 Colour sensitivity for an equi-energetic spectrum

4. Image quality

An optical diffraction method was used to determine the image quality of the holographic emulsion. A double-beam interference exposure enabled us to examine the resultant diffraction screen. Fig. 6 shows in schematic form both the exposure and the reconstruction.

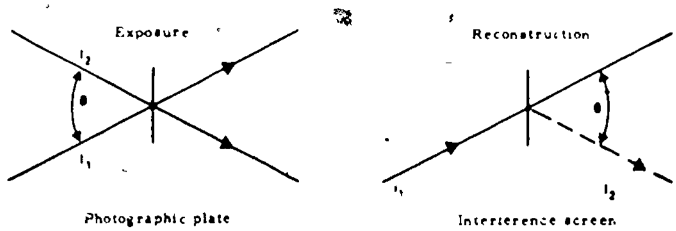

Fig 6 Schematic representation of exposure and reconstruction of double-beam interference

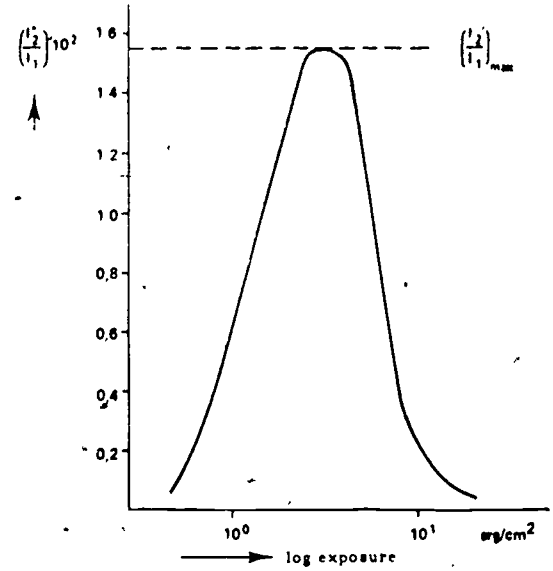

Fig 7 Dependence of diffraction efficiency on exposure

During exposure, two plane waves having intensities I_1 and I_2 were incident on the photographic plate, each at the same angle to the normal. Representing the angle between the two rays by θ, spatial frequency f is given by

$$f = \frac{2}{\lambda} \sin\left(\frac{\theta}{2}\right)$$

where λ = wavelength in air (633 nm for the He-Ne laser).

With $\theta = 90°$, a spatial frequency of 2,235 lines/mm will then result. The separation between adjacent lines will then be the inverse of the spatial frequency equal to approx. 0.45 micron.

Modulation m depends on the polarization of the laser radiation and intensity ratio I_1/I_2. In the case described, lasers with linearly polarized radiation were used. The electric vector was normal to the plane of incidence. The intensity ratio I_1/I_2 amounted to 0.5, corresponding to a modulation of 0.94. In general the modulation caused by the polarization considered here is

$$m = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}$$

Reconstruction took place as shown in Fig. 6. Ray I_1 was used for reconstructing ray I_2'. Intensity I_2' was a diffraction of the first order and hence ratio I_2'/I_1 is dependant on angle θ, modulation m, and the exposure. Fig. 7 shows ratio I_2'/I_1 against exposure.

This function has a definite maximum. Ratio I_2'/I_1 can be considered as a measure of the quality of a screen and is therefore called diffraction efficiency. Figs 8 and 9 show the optimum diffraction efficiency $(I_2'/I_1)_{max}$ as a function of the spatial frequency for Scientia emulsions 8 E 75, 10 E 75 and 8 E 56, 10 E 56 respectively. Intensities I_1 and I_2' have not been corrected for Fresnel reflection, because the latter corresponds to the practical applications of holography. The actual diffraction efficiency of the photographic emulsion for the polarization used is higher still, especially at large values of angle θ. We should mention that the material was over-modulated by using the large modulation values of 0.94 or 1. In other words, this is not a case of linear transfer; intensities of higher orders of diffraction are also obtained. In order to compare the diffraction intensity to noise I_N at various spatial frequencies, exposures were carried out with a single laser beam of the same overall intensity, and the photographic plates were all processed and measured under identical conditions. The resultant ratio I_N/I_1 is also shown in Figs 8 and 9.

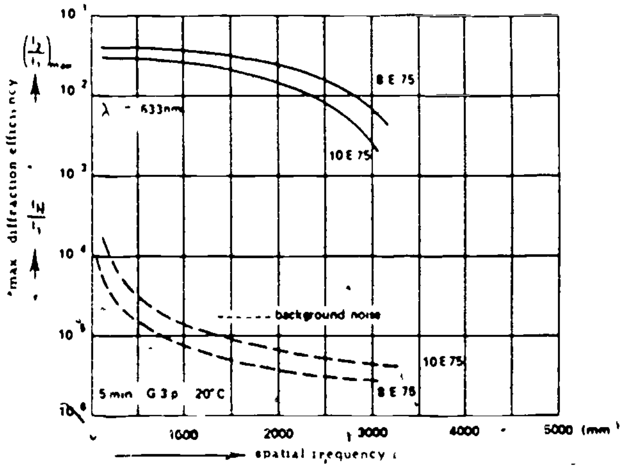

Fig. 8 Maximum diffraction efficiency against spatial frequency. E-vector normal to plane of incidence modulation 0.94

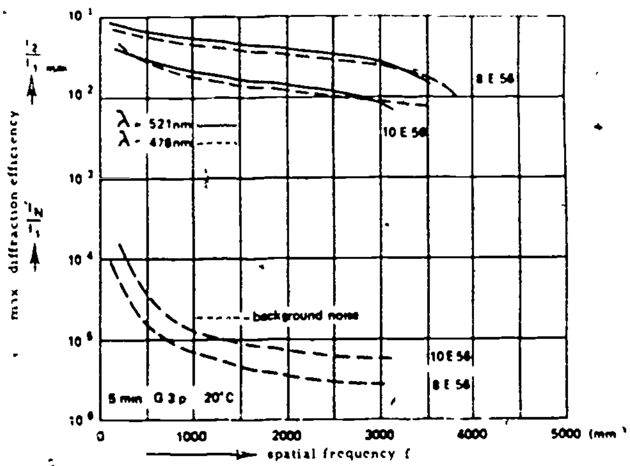

Fig. 9 Maximum diffraction efficiency against spatial frequency E vector normal to plane of incidence modulation m = 1.

5. Reciprocity behaviour

Q-switch lasers with pulsewidths of 10 to 50 ns are used for short exposures. In this case, the reciprocity behaviour of Scientia emulsions is obviously important. To obtain densities D < 2, the exposure of Scientia materials must be multiplied 2 to 4 times when Q-switch lasers are used.

6. Range

Emulsion		Sensitivity (erg/cm²)*	Plates	Films
10 E 75	He-Ne and ruby lasers	20	with or without antihalation layer	with antihalation layer
8 E 75		75		-
8 E 56	argon laser	150 - 300	antihalation layer in emulsion	-
10 E 56	krypton laser	10 - 20	with or without antihalation layer	without antihalation layer

* at $|T_a| = 0.5$ (see Section 2)

Base

- cellulose triacetate 0.14 mm with or without antihalation layer
- glass plates a) normal photographic glass
  b) provided at least 5 m^2 is ordered, also available on :
  - selected glass : max. plane deviation 25 μ/inch
  - plane glass : max. plane deviation 5 μ/inch

Your local Agfa-Gevaert agency will gladly supply information regarding sizes and prices.

Emulsion thickness

- on films 5 μ
- on plates 7 μ

Other thicknesses (e.g. 15 μ for Bragg (white light) holography) are available to special order. Conditions on request.

APPENDIX III

The Integration of Motion Pictures into Holograms

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We describe here a technique called integraphy which allows holograms to be made from standard two-dimensional motion pictures. The three-dimensional image can be seen through without the use of special spectacles and can be displayed in circular, continuous, linear, or other formats and the image seen can have 360° of perspectives.

There exist in published literature[1-5] various configurations for integrating still pictures into a holographic format. Collectively, they suffer from the following limitations: (1) The reference beam angle incident onto the hologram varies with the location of the hologram. This requires that the viewer must move his head in order to achieve a change in perspective (2) If a cylindrical hologram is desired, the recording system must also be cylindrical in configura tion, with the same radius as the final hologram desired (3) In no case has it been possible to have a continuous, non-repeating play of a holographic motion picture.

We wish to report a development which allows us to eliminate all of the above limitations.

Figure (1) shows the schematic layout of the system. The function of the polarization rotators is to orient the electric field vectors in such a way that they are parallel to one another and perpendicular to the plane formed by the two beams when they impinge onto the recording photographic emulsion. Figure (2) shows the top view of the object beam alone. The function of the cylindrical lens is to distort each point on the image plane into a horizontal line, but leaving the vertical component unaffected. The image is exposed, one strip at a time, corresponding to a frame of a motion picture. The function of the Fresnel lens is to collect the light from the screen onto the film in such a way that, in the event of a wide-angle scene, there would not be a fade-out at the edge. Typically, the scene recorded in the motion picture may be an event taking place on a rotating stage. Because each frame in the film represents a slight change in perspective of the scene, the subsequent image seen is three-dimensional due to the fact that each eye looks through a different strip. Since the recording holographic film is in the form of a continuous roll, the scene recorded on the motion picture can be continuous and the actions can be non-repeating. After the exposed film is processed it can be viewed by transporting it through a transparent circular drum, as shown in Figure (3), and illuminated concentrically from a point source below. Thus, the viewing angle is almost 360°. The distortion caused by the cylindrical lens in the recording stage is now compensated by the fact that the hologram is viewed in a cylindrical configuration The method thus allows the same system to be used for practically any cylindrical size, the only element to be changed in each case is the cylindrical lens.

Various cinematic techniques — such as fade-in, fade-out, zooming, multiple exposure, animation, computer generation, magnification, minification — are feasible.

Of special interest is a project presently under investigation in which the viewer is located inside the cylinder, looking outwards The motion picture is produced by panning the camera 360° on a stand. In this case stereoscopic views are available only if the camera is mounted eccentrically Through such a configuration, a 360° panoramic view of scenes, such as the Grand Canyon, can be recorded and displayed.

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2. N. George, J. T. McCrickerd, and M. M. T. Chang, Proc. SPIE Seminar-in-Depth Holography, p. 117 (1968).

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4. D. J. De Bitetto, Appl. Opt. 8, 1740 (1969).

5. L. Cross, private communications.

1974 Society for Information Display International Symposium
Digest of Technical Papers, Volume V (May 21, 22, 23, 1974)

The above paper was voted by those attended for the "BEST PAPER AWARD", presented during the 1975 Symposium held in Washington, D.C.