
Basic Principles and Applications of Holography

Tung H. Jeong
Lake Forest College
Lake Forest, Illinois

Holography is a much broader field than most people have perceived. Recording and displaying truly three-dimensional images are only small parts of it. Holographic optical elements (HOE) can perform the functions of mirrors, lenses, gratings, or combinations of them, and they are used in myriad technical devices. Holographic interferometry measures microscopic displacements on the surface of an object and small changes in index of refraction of transparent objects like plasma and heat waves. Future photonic devices such as electro-optical chips will undoubtedly incorporate micro-lasers and HOEs for optical computations, free-space interconnects, and massive analog and digital memory systems.

Prerequisites

To understand the concepts presented here, you will need to have studied Module 1-1, *Nature and Properties of Light*; Module 1-2, *Light Sources and Safety*; Module 1-3, *Basic Geometrical Optics*; and Module 1-4, *Basic Physical Optics*. In this module, a physical model will be developed so that all major features of basic holography can be explained through visualization and without the use of mathematics. Basic trigonometry will be helpful, but not required, for quantitative understanding.

Objectives

At the conclusion of the module, the student is expected to:

- Understand that there are two basic types of holograms—transmission and reflection.
- Know how to illuminate and view the two types of holograms.
- Be able to visualize the interference pattern between two point sources of light of the same wavelength and how this pattern changes depending on the relative position of the sources.
- Understand that making a hologram requires the recording of interference patterns between light from a fixed point source and light from each point on an object.
- Explain why the images of holograms are truly three dimensional.
- Know how to reconstruct the real and the virtual images from a transmission hologram.
- Understand why a transmission hologram can be broken into pieces and each piece can recreate the entire recorded image.
- Be able to make a reflection hologram and explain why the image can be viewed with incandescent light.
- Be able to make a transmission hologram with more than one channel of information and explain why.
- Understand the concept of coherence length as applied to laser light and holography.
- Define holographic interferometry.
- Know how to make a holographic diffraction grating with very high dispersive power.

Scenario—A day in the life of a holographer

Maria works for a company that has received a new contract from a software firm for producing 1,000,000 small holograms to be used as security seals on all its products. Having been trained as a holography technician, Maria is responsible for making the master hologram by using the three-dimensional model of a logo provided by the customer. She sets up the basic split-beam, focused-image, reflection-hologram configuration on the optical table and aligns the components using techniques learned in the holography course she completed in school. She produces an excellent holographic image of the logo that seems to stick out from the surface when illuminated with any point source of white light. She then hands the image to her friend, another technician in the replication department, who treats the hologram as if it were an original object and makes a million copies of it using rolls of photopolymers. All this is in a day's work for Maria and her friend.

Opening Demonstration

In a darkened classroom, demonstrate the properties of a reflection and a transmission hologram:

1. Use a point source of incandescent light—such as a “spotlight” available in hardware stores—and illuminate a typical white-light reflection hologram. Demonstrate the full parallax of the virtual image by allowing students to look up and down and left to right.

Now hold the emulsion side of the hologram on top of a cup of hot water (tea, coffee) and allow the steam to “swell” the gelatin. Observe the image again and notice that the color has been shifted toward red. This demonstrates that reflection holograms, although recorded on “black-and-white” photographic emulsion, can recreate three-dimensional images in color. This shows the essence of Lippmann photography (Nobel Prize in physics, 1908) and Bragg diffraction (Nobel Prize in physics, 1915).

2. Use a two-channel transmission hologram. Project a real image onto a screen using a *collimated* beam of laser light (or a laser pointer). Move the laser beam around the hologram and show that each spot recreates a distinctly different view of the object. Thus, if the hologram were broken into pieces, each piece would show a complete view of the recorded object.

Now change the angle of incidence on the same hologram and note that a completely different view appears—with all the same characteristics of the first image.

With use of a diode laser without the collimator, the diverging light can now be used to show the virtual image of each of the two channels in the hologram. Students must come up individually and look through the hologram as if it were a window with the object(s) on the other side. Point out that this demonstrates the enormous information-storage capability of holograms.

Basic Concepts

I. TYPES OF HOLOGRAMS

A *hologram* is a recording in a two- or three-dimensional medium of the *interference pattern* formed when a point source of light (*the reference beam*) of fixed wavelength encounters light of the same fixed wavelength arriving from an object (*the object beam*). When the hologram is illuminated by the reference beam alone, the *diffraction pattern* recreates the wave fronts of light from the original object. Thus, the viewer sees an image indistinguishable from the original object.

There are many types of holograms, and there are varying ways of classifying them. For our purpose, we can divide them into two types: *reflection holograms* and *transmission holograms*.

A. The reflection hologram

The reflection hologram, in which a truly three-dimensional image is seen near its surface, is the most common type shown in galleries. The hologram is illuminated by a “spot” of white incandescent light, held at a specific angle and distance and located on the viewer’s side of the hologram. Thus, the image consists of light **reflected** by the hologram. Recently, these holograms have been made and displayed in color—their images optically indistinguishable from the original objects. If a mirror is the object, the holographic image of the mirror reflects white light; if a diamond is the object, the holographic image of the diamond is seen to “sparkle.”

Although mass-produced holograms such as the eagle on the VISA card are viewed with reflected light, they are actually transmission holograms “mirrorized” with a layer of aluminum on the back.

B. Transmission holograms

The typical transmission hologram is viewed with laser light, usually of the same type used to make the recording. This light is directed from behind the hologram and the image is transmitted to the observer’s side. The *virtual image* can be very sharp and deep. For example, through a small hologram, a full-size room with people in it can be seen as if the hologram were a window. If this hologram is broken into small pieces (to be less wasteful, the hologram can be covered by a piece of paper with a hole in it), one can still see the entire scene through each piece. Depending on the location of the piece (hole), a different perspective is observed. Furthermore, if an undiverged laser beam is directed backward (relative to the direction of the reference beam) through the hologram, a real image can be projected onto a screen located at the original position of the object.

C. Hybrid holograms

Between the reflection and transmission types of holograms, many variations can be made.

- *Embossed holograms*: To mass produce cheap holograms for security application such as the eagle on VISA cards, a two-dimensional interference pattern is pressed onto thin plastic foils. The original hologram is usually recorded on a photosensitive material called *photoresist*. When developed, the hologram consists of grooves on the surface. A layer of nickel is deposited on this hologram and then peeled off, resulting in a metallic “shim.” More secondary shims can be produced from the first one. The shim is placed on a roller. Under high temperature and pressure, the shim presses (embosses) the hologram onto a roll of composite material similar to Mylar.
- *Integral holograms*: A transmission or reflection hologram can be made from a series of photographs (usually transparencies) of an object—which can be a live person, an outdoor scene, a computer graphic, or an X-ray picture. Usually, the object is “scanned” by a camera, thus recording many discrete views. Each view is shown on an LCD screen illuminated with laser light and is used as the object beam to record a hologram on a narrow vertical strip of holographic plate (*holoplate*). The next view is similarly recorded on an adjacent strip, until all the views are recorded. When viewing the finished composite hologram, the left and right eyes see images from different narrow holograms; thus, a stereoscopic image is observed. Recently, video cameras have been used for the original recording, which allows images to be manipulated through the use of computer software.
- *Holographic interferometry*: Microscopic changes on an object can be quantitatively measured by making two exposures on a changing object. The two images *interfere* with each other and fringes can be seen on the object that reveal the vector displacement. In *real-time holographic interferometry*, the virtual image of the object is compared directly with the real object. Even invisible objects, such as heat or shock waves, can be rendered visible. There are countless engineering applications in this field of *holometry*.
- *Multichannel holograms*: With changes in the angle of the viewing light on the same hologram, completely different scenes can be observed. This concept has enormous potential for massive computer memories.
- *Computer-generated holograms*: The mathematics of holography is now well understood. Essentially, there are three basic elements in holography: the light source, the hologram, and the image. If any two of the elements are predetermined, the third can be computed. For example, if we know that we have a parallel beam of light of certain wavelength and we have a “double-slit” system (a simple “hologram”), we can calculate the diffraction pattern. Also, knowing the diffraction pattern and the details of the double-slit system, we can calculate the wavelength of the light. Therefore, we can dream up any pattern we want to see. After we decide what wavelength we will use for observation, the hologram can be designed by a computer. This computer-generated holography (CGH) has become a sub-branch that is growing rapidly. For example, CGH is used to make holographic optical elements (HOE) for scanning, splitting, focusing, and, in general, controlling laser light in many optical devices such as a common CD player.

II. THE PHYSICAL BASIS OF HOLOGRAPHY

The Physical Model

To make holography accessible to a general audience with widely varied backgrounds, a physical model is useful. Just as chemists use sticks and balls to help them visualize the structure of molecules, our model will allow us to visualize, and thus “understand,” the physical characteristics of holograms without using advanced mathematics.

Two-Source Interference

In two dimensions (the plane of this paper), the pattern of waves from a stationary source generating waves at constant frequency (and wavelength) is a set of concentric circles (see Figure 3-2 [a] and [b] in Module 1-3, *Basic Geometrical Optics*, as an example of water waves). The distance between any two adjacent circles is one wavelength (λ). Let each circle represent the crest of a wave. Halfway between any two waves is the trough. The pattern shown in Figure 10-1 represents a snapshot of such a wave pattern.

Example 1

If we tried to visualize sound or light waves from a point source in space, what would an instantaneous pattern be?

Answer: The pattern would be a set of concentric *spheres*. The shortest distance between adjacent spheres is one wavelength.

To simulate the interference pattern caused by two point sources emitting waves at the same frequency and amplitude, let's make a transparent photocopy of the set of concentric circles shown in Figure 10-1. Then let's place the copy on top of Figure 10-1, move it around, and observe the results. A typical pattern is shown in Figure 10-2.

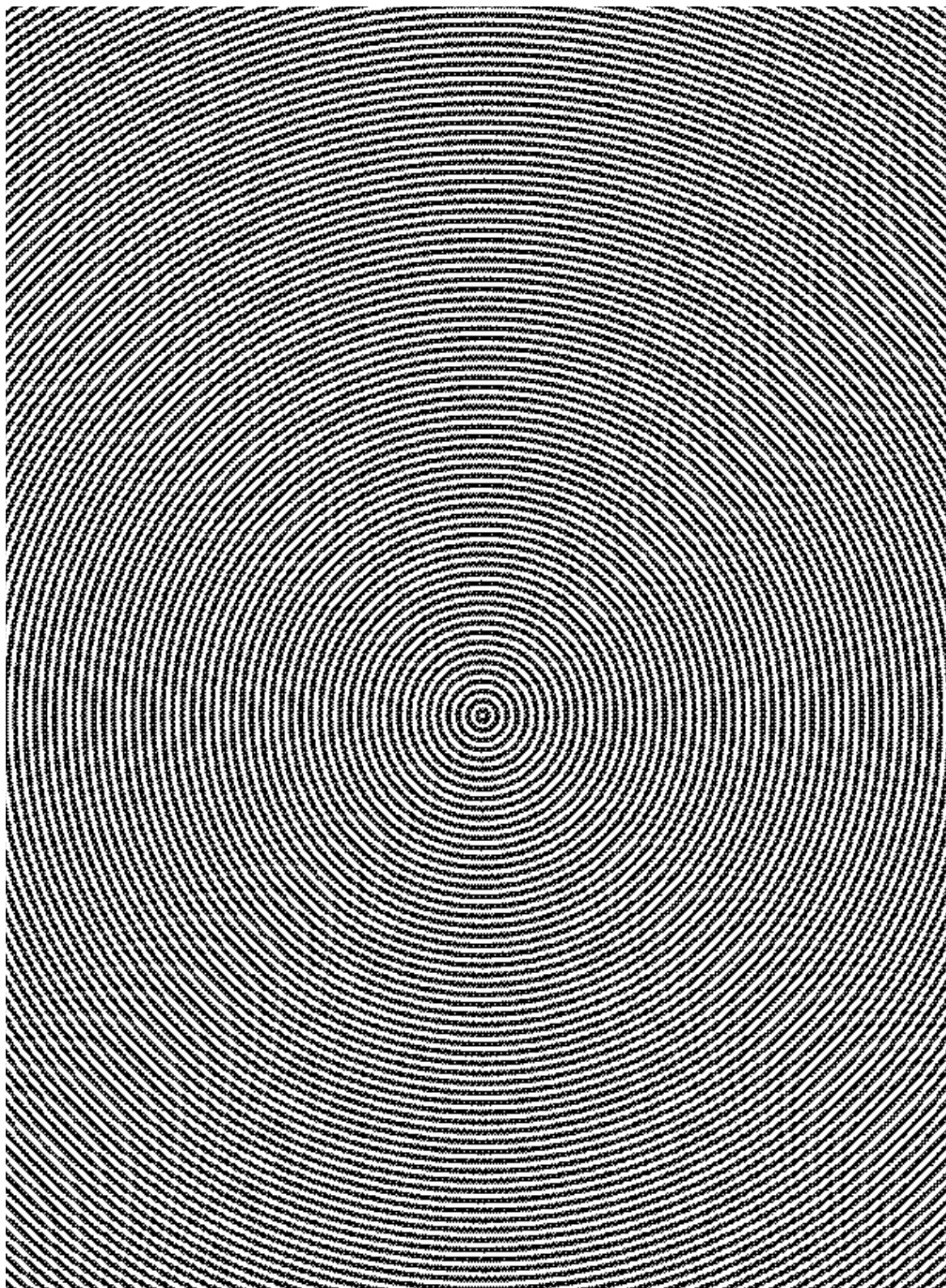


Figure 10-1 A two-dimensional “snapshot” of wave fronts from a constant-frequency point source at the center. The radial distance from one line to the next is one wavelength (λ).

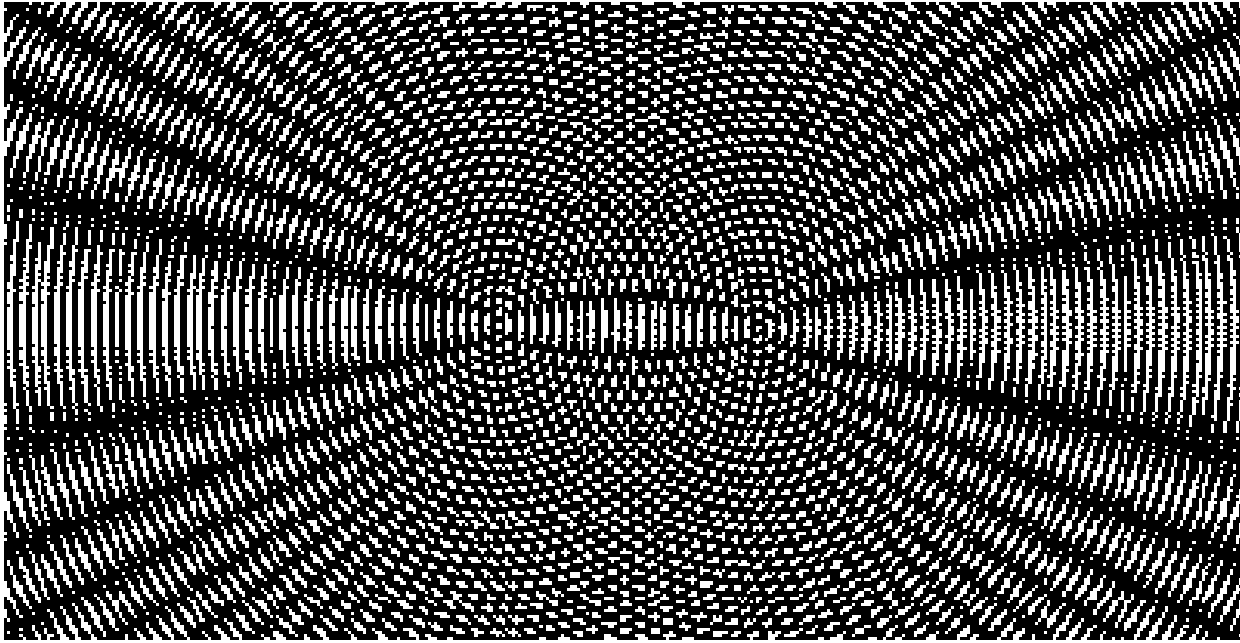


Figure 10-2 The two-dimensional interference pattern caused by two point sources of waves of constant frequency. Each set of waves is moving away from its source at the same constant speed. Nevertheless, the overall interference pattern remains constant in time. The two point sources creating this pattern can be seen near the center, along a horizontal direction, about four centimeters apart.

The *bright* (white) areas represent *constructive interference* because the crests from both sources—as well as the troughs from both sources—coincide, causing the waves to go up and down with twice the amplitude of each wave alone. The *dark* (black) areas represent *destructive interference* because the crest of one wave encounters the trough of the other wave, thus causing a cancellation of wave amplitude at that point. For water waves, the center of each dark area represents perfect and *permanent calm* in spite of the fact that waves from the two sources are passing through the dark area at all times. For sound waves, the same areas would represent regions of absolute silence.

A Trace of the Maxima from Two Point Sources

Figure 10-3 represents a trace of the constructive interference maxima—the white regions—observed in Figure 10-2. Here, S and S' denote the locations of the centers of the two sources. At precisely the midpoint between S and S' is a straight line OO' . At any point along this line, waves arriving from the two synchronized sources meet exactly in phase (or have zero phase difference), since they have traveled the same distance. This is called the *zeroth order* of constructive interference. For *all* points on the first curved line PP' (a hyperbola) at the right of the zeroth-order line, waves from S' travel a distance exactly one wavelength more than waves from S . Thus, this line represents the location of the *first order* of constructive interference. Similarly, the first curved line at the left of the zeroth order is also a first-order constructive interference pattern.

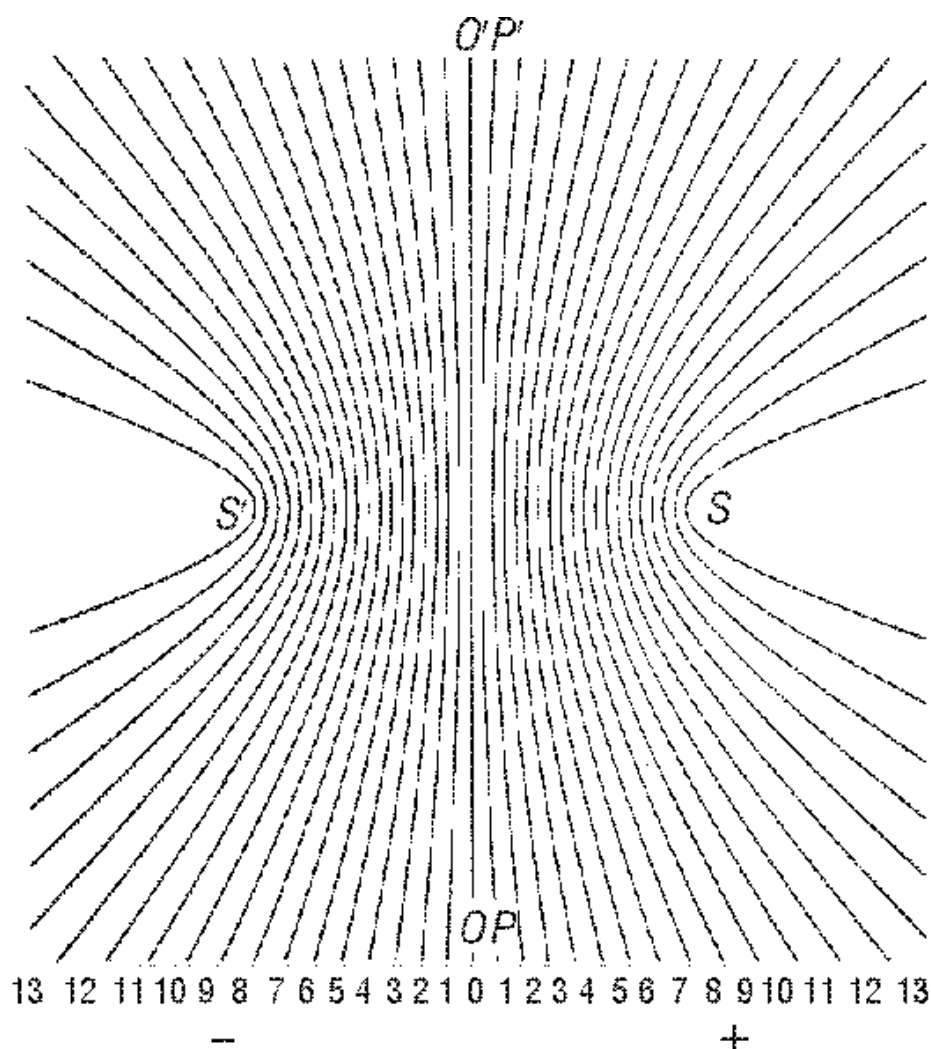


Figure 10-3 A computer trace of the locations of interference maxima on a plane containing the two point sources S and S'

Thus, the tenth curves at the left and right of the zeroth order are *tenth orders* of constructive interference. Any point on these curves has a difference in distance from S and S' equal to 10λ .

Exactly halfway between consecutive orders of interference maxima are hyperbolas (not drawn in Figure 10-3), which represent the *minima*, where the wave amplitude is always zero in spite of the fact that waves from two sources of disturbance are continuously passing through. In other words, waves meeting at any point along any line in Figure 10-3 are *in phase*. And waves meeting at any point along lines halfway between the constructive interference lines are *out of phase* and result in zero amplitude.

Now, suppose we imagine the interference pattern from S and S' as it exists in space, that is, in *three dimensions*. Figure 10-4 represents a cross section of this three-dimensional interference pattern. If the pattern were to spin around the x -axis, one would observe a set of *hyperboloidal surfaces*. The zeroth order ($m = 0$) is a flat plane, and all other orders ($m = 1$ and higher) are

smooth surfaces of varying curvatures. On the x - y and x - z planes are interference patterns like those shown in Figure 10-3, a set of hyperbolas. On the y - z plane, as shown in Figure 10-4, the pattern is a set of concentric circles.

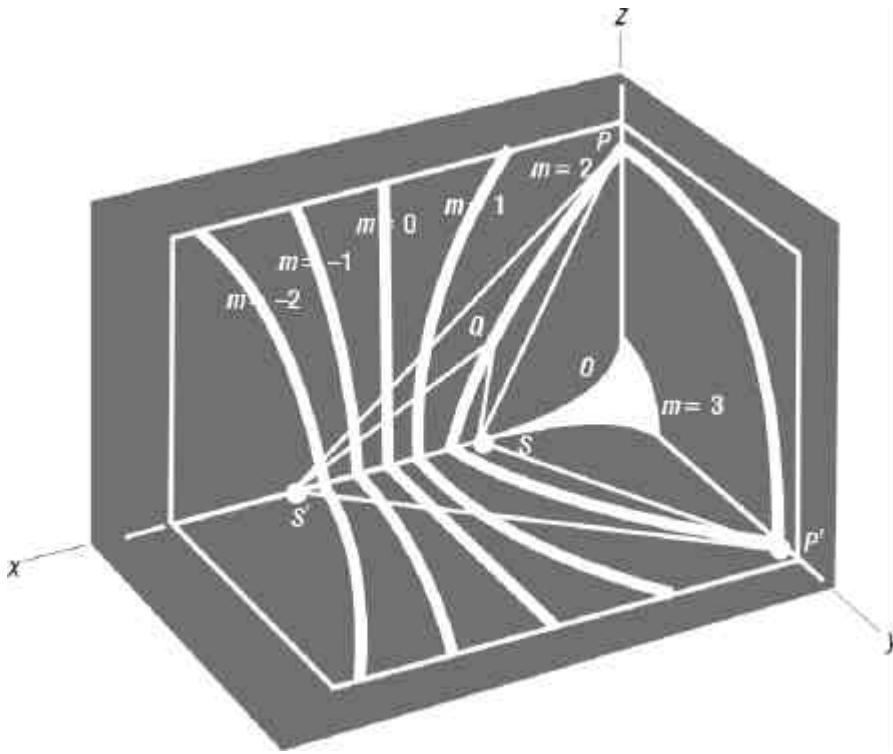


Figure 10-4 A three-dimensional interference pattern of waves from two point sources S and S' . The constructive interference order numbers, m , are indicated for the first several maxima.

Using the transparency of circles of Figure 10-1 that we made earlier, and placing it again on top of the original set (Figure 10-1), we can demonstrate how uniquely different interference patterns are formed—corresponding to each unique location of S versus S' . Observing the pattern along the axial direction (line through S and S') reveals the concept of *Michelson interferometry*. Far above and below S and S' , *Young's double-slit interference pattern* is recreated. Changing the distance between S and S' shows how the pattern changes correspondingly. For example, as the separation between S and S' increases, the interference fringes become more dense, i.e., more maxima and minima per unit distance. This is measured in terms of *spatial frequency*, or cycles per millimeter. Conversely, as the distance between S and S' decreases, the spatial frequency of the interference pattern decreases—less cycles per millimeter.

Example 2

Verify the statement in the above paragraph by moving the *transparency of circles* around on top of the page with circles (Figure 10-1).

The Physical Model

Some interesting characteristics of *hyperboloids* are represented in Figure 10-5. Think of the separate hyperboloids as the three-dimensional surface traced out when Figure 10-3 is rotated about an axis through the points SS' . Imagine that all the hyperboloidal surfaces are mirrors. Take the zeroth-order “mirror” OO' , which perpendicularly bisects the line SS' joining the two sources. In three dimensions, this is a flat mirror. Each ray from point S , striking the hyperboloidal surface (mirrors) at $m = 2$, $m = 1$, $m = 0$, $m = -1$, and $m = -2$, as shown, reflects from these surfaces (mirrors) in a direction such that the reflected ray appears to come from point S' . Two such rays from S are shown in Figure 10-5, one up and to the left (labeled a), the other down and to the left (labeled b). The reflected rays are labeled $a_0, a_1, a_2, a_{-1}, a_{-2}$, and b_2 and b_1 , in accordance with the appropriate ray from S and the hyperboloid from which they reflect. Thus, S' is the *virtual image* of S , for any and all of the surfaces. The reverse is true for light from S' incident on the surfaces, for which S would then be the virtual image.

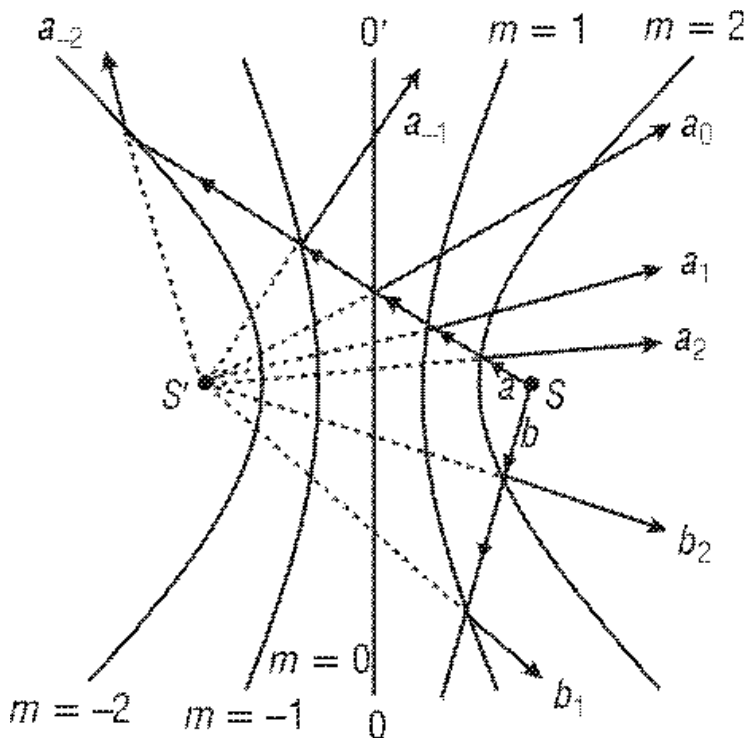


Figure 10-5 Light from S is reflected by any part of any hyperboloidal surface (mirror) in a direction such that it appears to be originating from S' .

With this physical model in mind, we are now ready to explain all the important characteristics of holograms recorded in a medium such as photographic emulsion that has a thickness of about 6 to 7 micrometers (μm).

Applications of the Model

Creating the Virtual Image

Figure 10-6 shows the optical case of two-beam interference in three-dimensional space.

Assume that the light from the two sources (S and S') is directed at a recording medium such as a silver halide photographic emulsion (“*holoplate*”) at a position as shown. The flat rectangle in the figure represents the top edge of the holoplate. Since the typical thickness of these emulsions is in the vicinity of 6 or 7 μm and the wavelength of laser light used to record holograms is 0.633 μm (HeNe laser), this thickness is approximately 10λ . *The interference pattern recorded inside the emulsion represents sections of hyperboloidal surfaces of many different orders of m .* These are, of course, sections of the hyperboloidal surfaces that we have been describing.

Observe carefully the orientation of the “mirrors” formed inside the emulsion. The “mirrors” on the left side lean toward the right, those on the right side lean toward the left, and those in the center are perpendicular to the plane of the holograms. In precise terms, *the plane of each “mirror” bisects the angle formed between rays from S and S'*

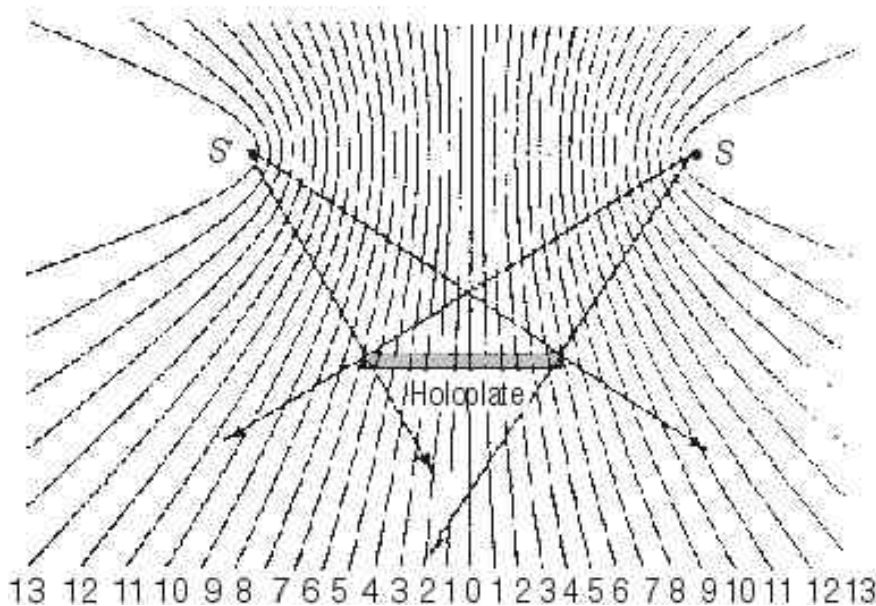


Figure 10-6 Light from S interferes with light from S' and produces a three-dimensional interference pattern inside a “thick” medium such as photographic emulsion (the “*holoplate*”).

The exposed and developed emulsion (holoplate) is called a *hologram*. Within the hologram, the recorded silver surfaces are partially reflecting—as well as partially transmitting and absorbing. If we replace the hologram in its original position during the recording, take away S' , and illuminate the hologram with S alone, as shown in Figure 10-7, all the reflected rays will appear to originate from S' . An observer would see these reflected rays as if they all came from S' . In other words, *the virtual image of S has been created.*

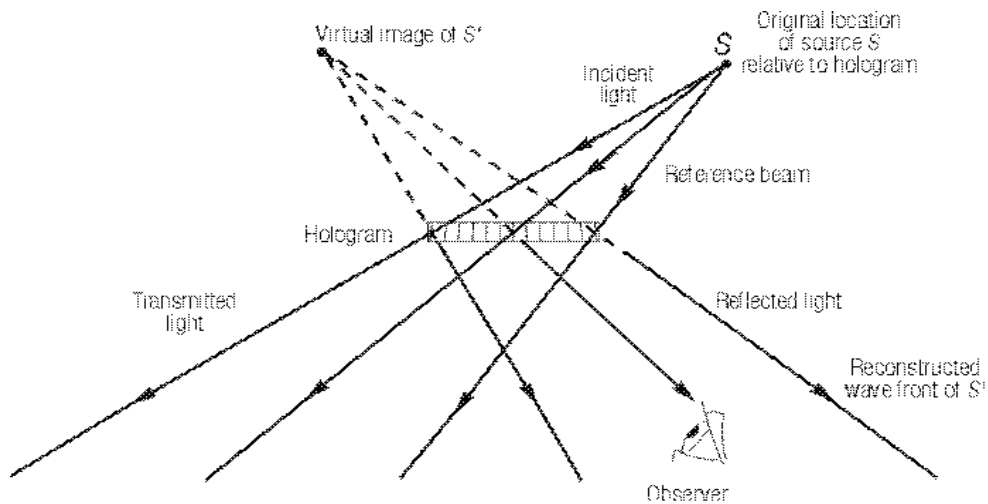


Figure 10-7 When the developed emulsion (hologram) is illuminated by S alone, the virtual image of S' is observed.

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

If we replace point source S' with a three-dimensional scene (or object) illuminated by light having the same constant frequency as the reference beam, each point on its surface (S_1' and S_2' , for example) creates a unique hyperboloid set of patterns with S inside the emulsion. Thus, we have a hologram of a three-dimensional object (Figure 10-8). When the hologram is illuminated by S , each set of hyperboloidal mirrors recreates a virtual image of each point (S_1' , S_2' , etc.), so that a complete, three-dimensional virtual image of the object is reconstructed.

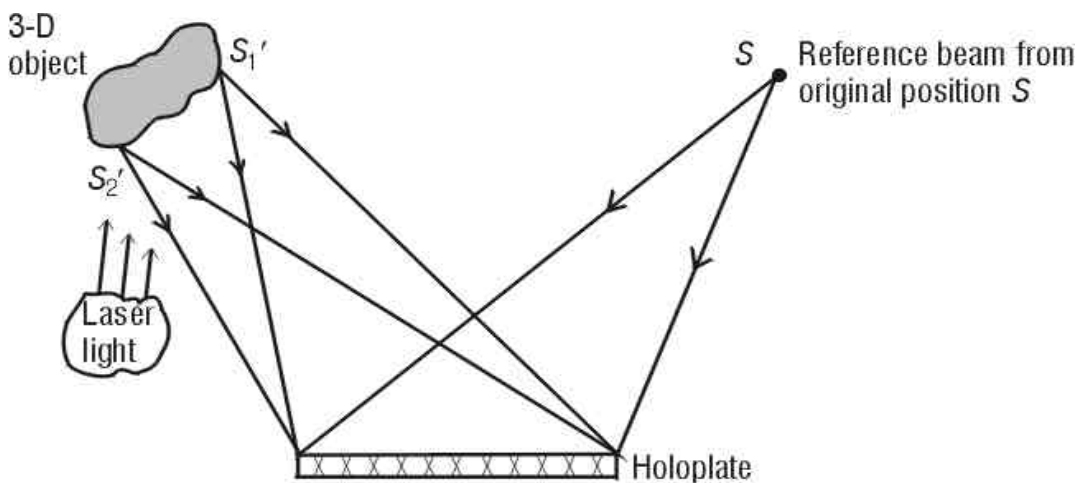


Figure 10-8 A hologram of a three-dimensional object can be considered as a superposition of many individual holograms of points on an object.

A general statement of the model can now be given as follows:

Imagine all hyperboloidal surfaces that represent the interference maxima due to two interfering sources to be partially reflecting surfaces. When a hologram is made, the volume throughout the emulsion records a sum of a multitude of hyperboloidal sets of partial mirrors, each set being created by the interference between the reference beam (S) and light from each point on the object (S_1', S_2', \dots, S_n'). When the hologram is viewed by illuminating it with S , each mirror set reflects light and forms a virtual image of each object point, thus recreating the wave front of the original object.

Creating a Real Image

Take the hologram from Figure 10-7 and illuminate it in a “backward direction” by focusing a beam of light back toward S (Figure 10-9). The reflected light from our hyperboloidal mirrors will focus at S' so that, if a projection screen were present there, we would have a *real image* of the original 3-D object. This can be done also with the hologram formed in Figure 10-8. The real image in this case will appear on the screen as a two-dimensional image of our original object. Depending on the location of the screen, different slices of this scene will come into focus.

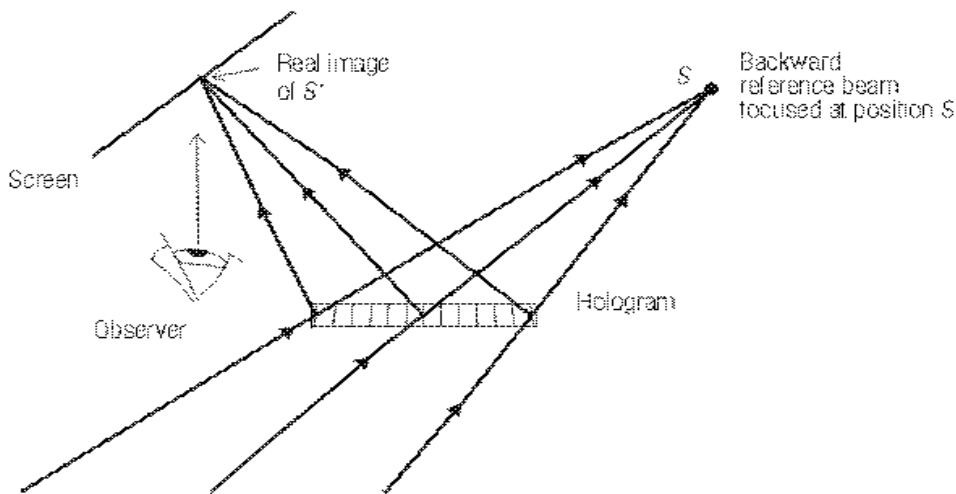


Figure 10-9 If a hologram is illuminated from the “front,” exactly backward toward S , the hologram will reflect the light behind the hologram to form a real image of S' on a screen.

Redundancy

If a transmission hologram is broken into pieces, each piece will give a complete perspective of the original scene. This can be understood from Figure 10-10. Imagine that the holoplate were half or a small fraction of its original size shown earlier in Figure 10-8. 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 holoplate used to make a hologram is independent of the size of the scene. *A large hologram can be considered as the sum of many smaller holograms.*

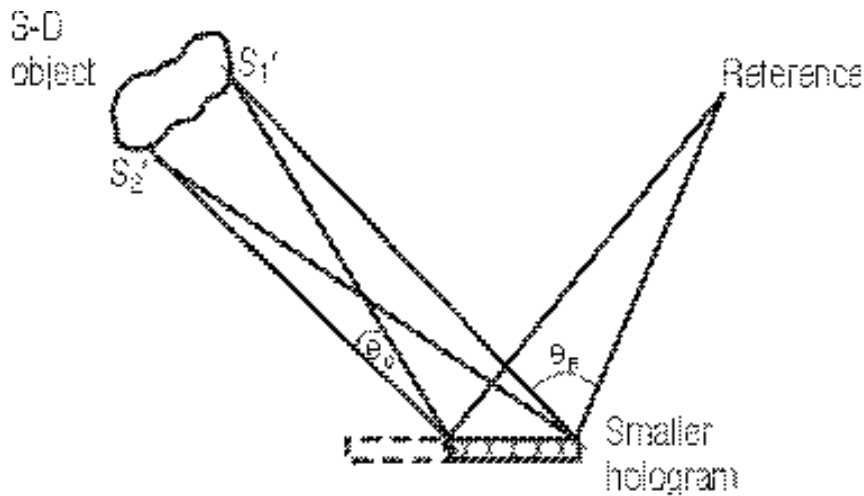


Figure 10-10 Each piece of a hologram can recreate a complete view of the object. A large hologram can be considered as a collection of many smaller holograms.

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., *aperture*, *depth of field*, and *resolution*.

Dynamic Range

Not only the locations of all points on an object are reproduced in the hologram, but their relative intensities as well. Consider two spots S_1' and S_2' on the object, with S_1' having the same intensity as S and S_2' being less intense than S (Figure 10-11). In the areas where the light waves from S are in phase with those from S_1' , the total amplitude is doubled. Where they are out of phase, the total amplitude is zero. The same cannot occur between waves from S and S_2' . The result is that the interference pattern formed between S and S_1' has a higher contrast than those formed between S and S_2' , and results in having “mirrors” with higher reflectivity. In other words, S_1' simply makes a brighter hologram than S_2' .

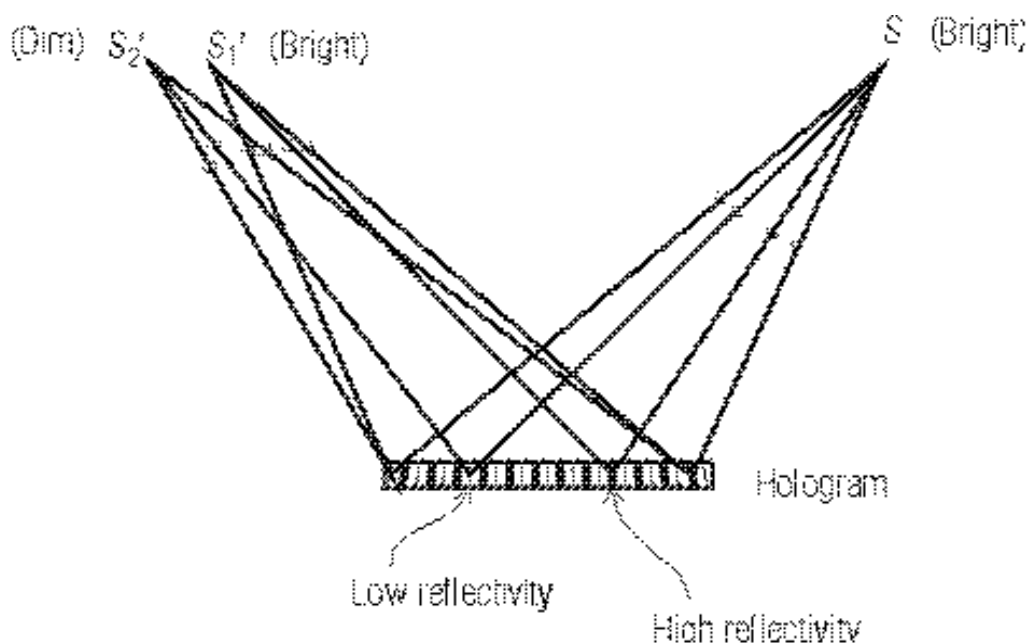


Figure 10-11 A bright spot S_1' creates a brighter hologram with S than does a dim spot S_2' .

Thus, a hologram can recreate images with intensity levels varying from almost complete darkness to glares. The holographic image of a diamond, for example, can be seen to “sparkle.” The hologram is said to have a large *dynamic range*.

By contrast, a photograph (or a TV picture) cannot reproduce glares or sparkles. The brightest part of such an image is the diffused white color of paper (or screen).

“Noise”

As is true in all information-transmission systems (radio, TV, recording a picture, etc.), the output always has *background noise* added to it. Similarly, a copy of a photograph is never as high in quality as the original.

Besides the so-called grain “noise” of photographic emulsion, which is caused by the scattering of light by the silver grains, another source is called *intermodulation noise*. In Figure 10-11, in addition to the interference patterns formed between S and S_1' , and S and S_2' , there is a pattern formed between S_1' and S_2' (not shown). The latter pattern forms a set of hyperboloids throughout the volume of the emulsion but of much lower spatial frequency (fewer lines per millimeter across the surface of the film due to the close proximity between S_1' and S_2'). These extra “mirrors” direct light in arbitrary directions when the hologram is illuminated with S alone, and create a background of “fog.”

When the scene consists of a three-dimensional object, each pair of points on the object creates a set of *unwanted interference patterns*. With a small object located far from the hologram, the range of angles between pairs of points (S' and S'') on the object is small and the noise problem is not severe. In the extreme case where the object is simply a point source S' , there is no intermodulation noise at all.

On the other hand, a large object situated near the hologram can create severe noise problems because every pair of points on it creates a set of unwanted interference patterns. Referring to Figure 10-8, light from S_1' and S_2' will interfere throughout the emulsion. The larger the object and the closer it is to the hologram, the higher the spatial frequency of its interference patterns (i.e., more mirrors created), along with the increase in the severity of the noise problem.

Beam Ratio

To help minimize the effects of intermodulation noise, practical holography requires that the reference beam be of higher intensity than light from any point on the object. In practice, the intensity ratio—as measured (at the location of the holoplate) by using a diffuser in front of a light meter, between the reference and object beams—varies from 1:1 to 10:1 for *transmission holograms*, the type so far under discussion. This allows the “mirrors” to form due to light from the reference beam and points on the object to be generally of higher reflectivity than those formed due to light from 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 (θ_R in Figure 10-10) be greater than the largest angle formed by a pair of points on the object (θ_O in Figure 10-10). This ensures 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 intermodulation noise is diverted to angles smaller than the signal. In this way, even though we cannot eliminate the noise, we can isolate it. In engineering terms, we have spatially isolated the *frequency domains* of the signal from the noise. In doing so, we have increased the signal-to-noise ratio, i.e., increased the quality of the hologram.

Multiple Scenes

One of the most dramatic features of a hologram is that it is capable of recording more than one independent scene in the same volume of space and then displaying them independently by changing the angle between the hologram and the reference beam. This phenomenon was discovered by a father and son team (William Henry and William Lawrence Bragg) through the study of X-ray diffraction by crystals. They were awarded the 1915 Nobel Prize in physics.

To understand what follows, it is necessary to review the subject of *thin-film interference* (Module 1-4, *Basic Physical Optics*) and be able to explain what causes the beautiful colors when diffused white light is reflected by soap bubbles.

Figure 10-12 shows a realistic cross-sectional view of the interference pattern formed in a microscopically small piece of hologram created using the configuration shown in Figure 10-5. (For simplicity, Snell refraction [Module 1-3, *Basic Geometrical Optics*] has been ignored by assuming that the hologram is sandwiched between material with the same index of refraction as the emulsion.) The hyperboloidal surfaces inside the thin emulsion layer approach flat planes and are perpendicular to the film surface, like venetian blinds in the “open” position. Because of the large angle between rays from S and S' (about 90°), the separation between “mirrors” is about λ , much smaller than the emulsion thickness of 10λ . Here, λ represents the wavelength of light *inside the medium*.

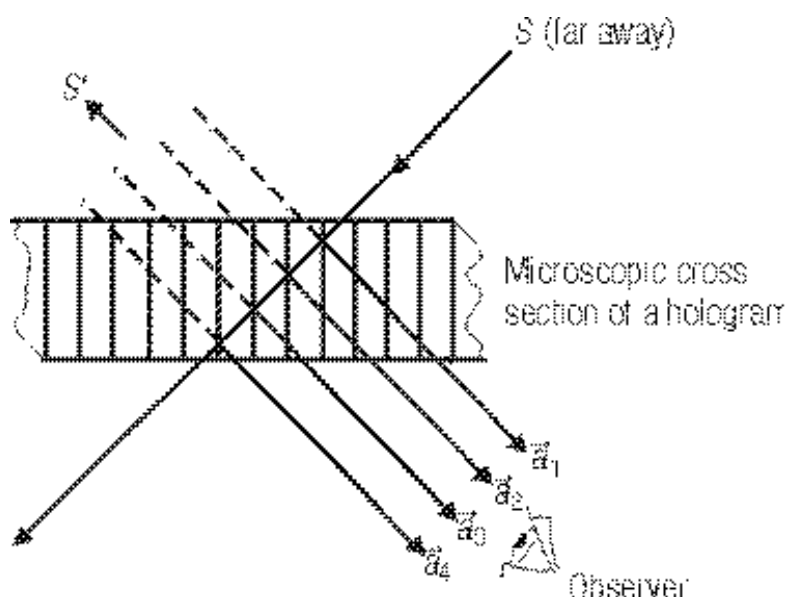


Figure 10-12 A microscopic cross section of a hologram. The thickness of the hologram far exceeds the distance between interference orders, and light from S undergoes multiple reflections.

When the hologram is viewed with S alone, the light undergoes multiple reflection by successive planes when it penetrates the film. However, because of the inherent characteristics of this family of hyperboloid “mirrors” (recall Figure 10-5), each successive reflection will have a precise phase shift of 2π because the optical path is increased by precisely the distance of one wavelength. All the reflected waves are precisely in phase and, therefore, add in amplitude, resulting in a strongest possible wave front representing the object beam. If the angle of incidence of S is deviated from the original reference beam relative to the hologram, all the multiply reflected beams will have phase differences other than 2π and the resultant reflected wave will be much lower in intensity, even zero.

Quantitatively, we can state that, in the case of correct illumination, the absolute values of all the amplitudes— a_1, a_2, \dots, a_n , of successive reflections—add directly and the intensity is $I = (|a_1| + |a_2| + \dots + |a_n|)^2$. In the case of misaligned illumination, the phase shift of each successive reflection is different from 2π and $I' = (\bar{a}_1 + \bar{a}_2 + \bar{a}_3 + \dots + \bar{a}_n)^2$, so that $I > I'$ always.

In practice, when the illuminating angle is significantly different from the correct angle, no image can be seen.

This phenomenon—*Bragg diffraction*—is of great historical significance. Using a beam of X rays of known wavelength, directing it at a crystal such as rock salt, and studying the angles of maximum diffraction, the distance between the atomic layers was measured. In turn, using crystals with known atomic spacing, X-ray wavelengths were accurately measured. This allowed scientists to study the inner workings of the atom.

In modern photonics, this principle is used to design multilayer thin films on mirror surfaces such as those used in laser cavities, to make optical fibers that selectively transmit and reflect chosen wavelengths, and to fabricate exotic crystal for massive holographic memories.

To create multiple-scene holograms (see the laboratory for making two-channel transmission 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 a second time. Generally, each exposure time 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 wave front of one *or* the other scene can be recreated. This is true for both the real and the virtual images.

Depending on the thickness of the emulsion, the sizes of O_1 and O_2 , and their proximity to the film, different degrees of success can be achieved in recording multiple images with minimum “cross-talk” (image overlap).

It is interesting to compare *time-domain* versus *space-domain* in information systems. A long song takes a long *time* to sing; a long written story requires a thick book (large *volume*) to record.

Example

Suppose a 1.0-mm-thick CD can store 1.0 gigabyte of information in the form of digital data. All these data are stored in the top 1.0-micrometer-thick layer. How much information can this CD store if it can record over its entire volume at the same information density?

Answer: 1.0 terabyte

The CD is 1000 micrometers thick and it uses only the 1.0-micrometer top layer to store the 1.0-gigabyte information. The remaining 999 layers can store an additional 999 gigabytes, leading to a total of 1000 gigabytes or 1 terabyte.

White-Light Reflection Holograms

Gabriel Lippmann received the 1908 Nobel Prize in physics for his discovery of recording color photographs on a “black-and-white” silver halide emulsion. Today, we use a similar “Lippmann emulsion” for recording holograms.

Figure 10-13 shows a photographic camera in which the lens focuses a colorful object on the recording emulsion several micrometers in thickness. The back of the emulsion is in physical contact with a pool of mercury, which serves as a mirror and reflects back all light incident on it.

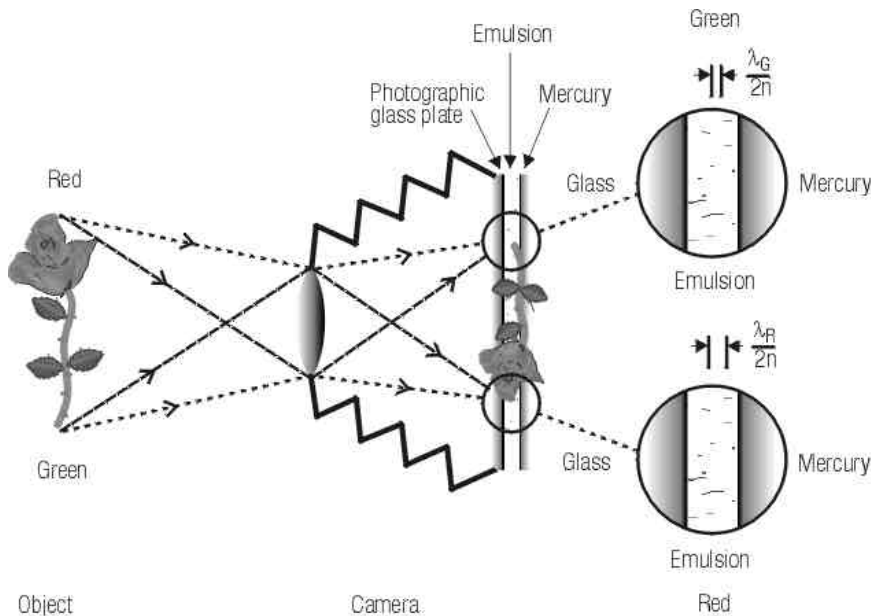


Figure 10-13 Lippmann photographs are recorded in a camera in which mercury is used to reflect the light back through the emulsion to create a standing wave for each color of light.

Suppose that the image of the petal of a red rose falls in a particular region of the emulsion. The red light traverses the emulsion and is reflected back through it. The incident red light interferes with the reflected red light and forms a *standing wave* in which the distance between adjacent maxima (or minima) is $\frac{1}{2}\lambda$. In another area of the emulsion, a green leaf is focused there, forming an image. The green light similarly forms a standing wave pattern throughout the emulsion. Because green light has a shorter wavelength than red light, its interference pattern is of a higher spatial frequency. Another, still higher-frequency, pattern may be formed elsewhere where a patch of the blue sky is focused.

After the photograph is developed, layers of silver remain in all locations where the maxima of all the interference patterns are located. When illuminated with a patch of white light, each area of the photograph reflects—by constructive interference—a color corresponding to the original focused image. The result is a full-color photograph recorded in a colorless emulsion.

With the availability of highly coherent laser light and an improved Lippmann emulsion, we can use the same concept to record three-dimensional scenes in color.

Figure 10-14 shows again the overall interference pattern between point sources of coherent lights S and S' . Note that the region between S and S' is occupied by *standing waves*, where the distance between adjacent maxima (or minima) is $\frac{1}{2}\lambda$. If we place a 10λ -thick emulsion midway between the sources (where MN and PQ are surfaces at the opposite sides of the emulsion) and record the interference pattern, we will have 20 hyperboloidal surfaces throughout the hologram. When illuminated by S alone, a virtual image of S' is created—and vice versa—as discussed earlier.

Recall that the *interference patterns* recorded in a *transmission hologram* consist of slivers of hyperboloidal “mirrors” (Figure 10-6) that are *perpendicular* to the plane of the emulsion, like venetian blinds in the “open” position. In a reflection hologram (Figure 10-14), the “mirrors” are

parallel to the plane of the emulsion. Furthermore, the latter has twenty mirrors—for a 10λ -thick emulsion, as explained above—whereas the other has only four (Figure 10-12) when each is being illuminated by its reference beam.

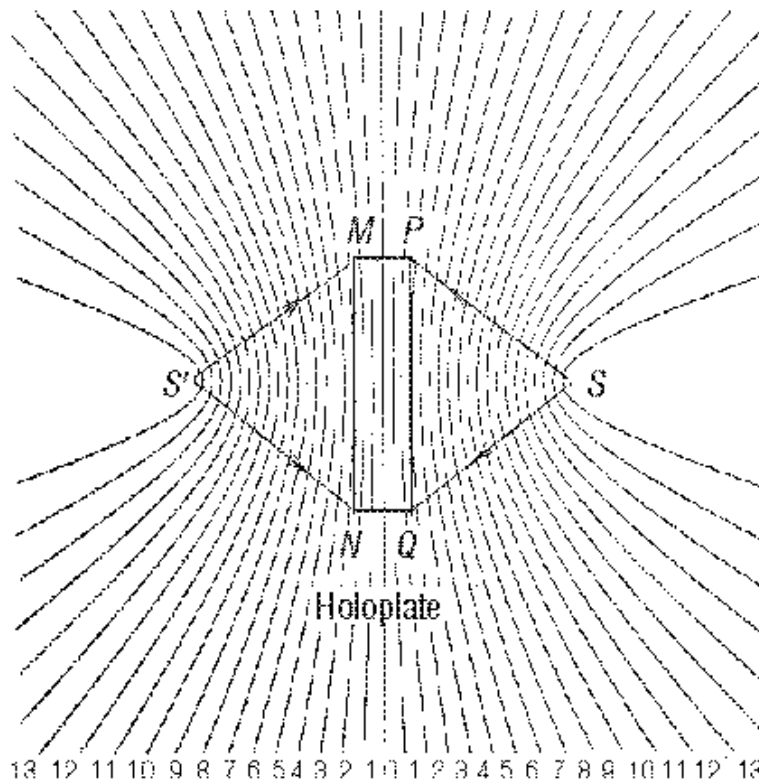


Figure 10-14 Reflection holograms are recorded in the region between the reference and object beams where standing waves are created. MN and PQ are surfaces on opposite sides of the emulsion. (Only a portion of the “mirror” surfaces is shown between planes MN and PQ.)

The result is that the reflection hologram can be viewed with incandescent light located at S , due to the fact that the additional sixteen “mirrors” strongly select the same wavelength of the laser that recorded them.

Example

A reflection hologram is made with red laser light. However, when illuminated with white light, the image appears yellow, or even green. Why?

Answer: The emulsion shrinks when the hologram is developed and dried. This causes the spacing between the hyperbolic surfaces to be decreased. Thus, a shorter wavelength is being reconstructed. Placing the hologram on top of a cup of hot coffee will swell the emulsion, and the color of the image can be tuned back to red momentarily.

Figure 10-15 shows the simplest method of making holograms: A solid object is placed in contact with the holoplate, with the emulsion side facing the object. Light spreading from a

diode laser (located at point S) is allowed to expose the emulsion. Light that passes through the holoplate illuminates the object. Each point on the object scatters light back through the emulsion and interferes with the direct light from S , creating a set of unique hyperboloidal “mirrors” throughout the volume of the hologram.

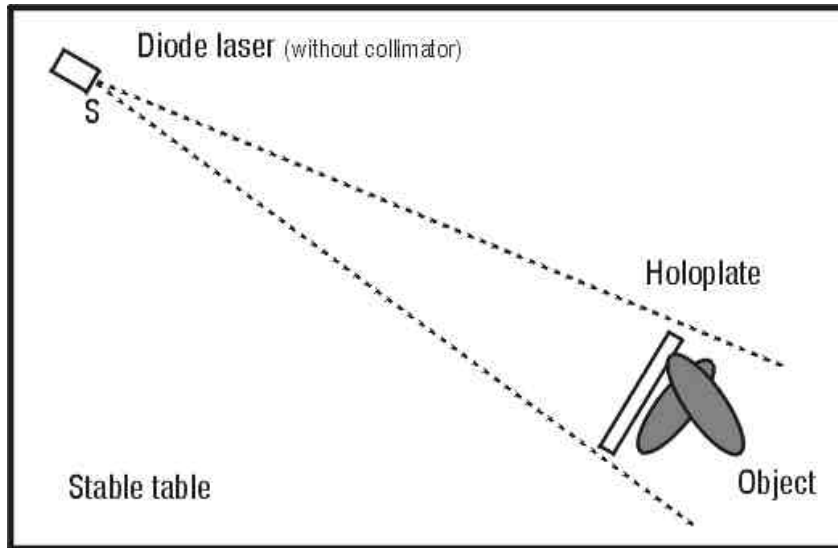


Figure 10-15 Simplest method of making a hologram: The spreading light from a diode laser interferes with the light scattered back by the object and forms standing waves throughout the volume of the recording medium.

When the developed hologram is illuminated by a point source of incandescent light, each set of hyperboloidal “mirrors” reconstructs a virtual image of a point on the object. Together, all the sets of “mirrors” reconstruct the entire three-dimensional image in a single color.

To make full-color holograms, light from three lasers (red, green, and blue) is combined into one single beam and the hologram is recorded in the same way as above. However, a special development process is required to ensure that there is no shrinkage in the emulsion.

At this point, let’s compare the main differences between transmission and reflection holograms: *transmission holograms are made with both reference and object beams on the same side*; the interference patterns recorded are like venetian blinds and are more or less perpendicular to the surface of the hologram. On the other hand, *reflection holograms are made with the reference beam on the opposite side of the object beam*. Its hyperboloidal fringes are more or less parallel to the surface of the hologram.

Since the entire object is on the same side of any hologram, any pair of points on it creates unwanted *intermodulation noise* by forming a transmission type of interference pattern. Therefore, when a reflection hologram is illuminated, the intermodulation noise is transmitted to the side away from the observer, while the image is reflected toward the observer. *Thus, in making reflection holograms, the best beam ratio is one-to-one* because we can ignore the intermodulation noise.

Holographic Interferometry

Consider a “**double exposure**” as represented by Figure 10-16a. Here the object is located at S_1' during the first exposure. It is then moved to S_2' , a distance of the order of a few λ 's, for the second exposure. The resultant hologram is a superposition of two sets of hyperboloids that coincide on the left side of the hologram but fall in between one another on the right side.

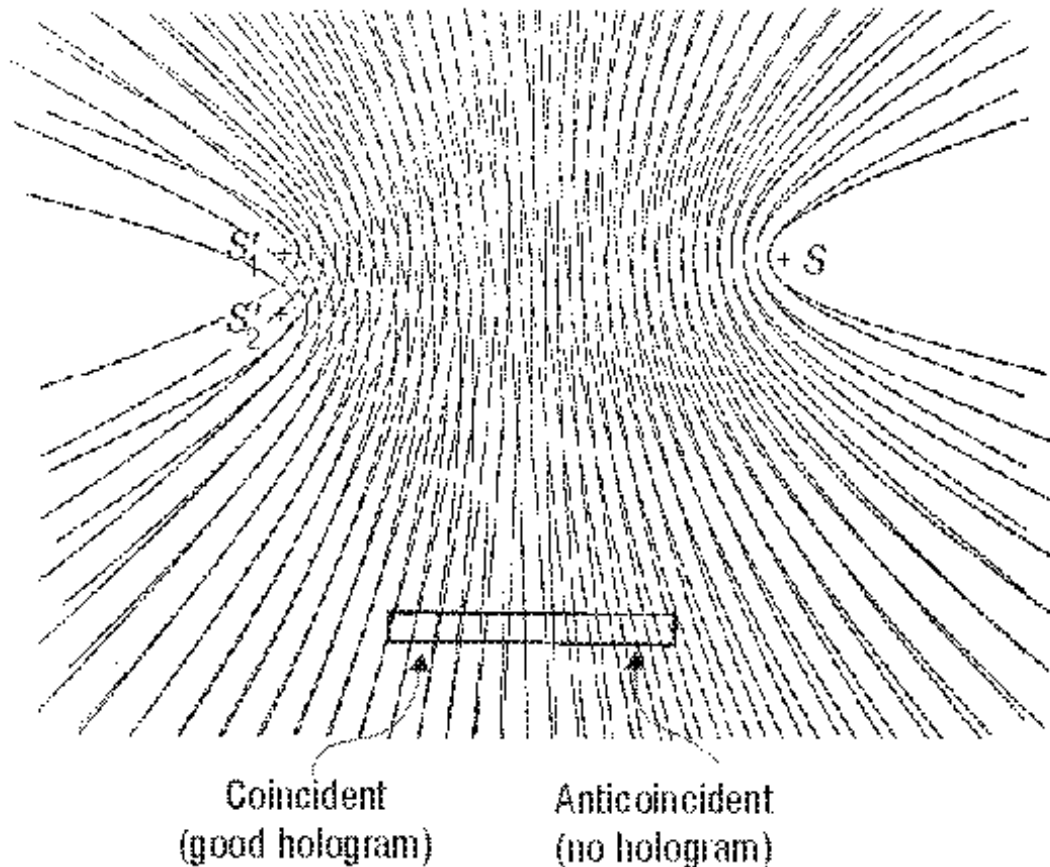


Figure 10-16a A double-exposure hologram of S' in two locations. The two interference patterns are coincident at the left of the hologram but are anticoincident at the right side.

When the virtual image of the hologram is reconstructed by S , a bright point located in the vicinity of the original object is seen from the left side of the hologram. As the viewer moves toward the right side of the hologram, the object S' disappears! The reason is that, at the right side, the two superposed interference patterns cancel each other when the maxima of one set fall in the positions of the minima of the other set.

If the object point had been displaced differently (from S_1' to S_3' , as shown in Figure 10-16b), its interference pattern would be shifted in such a way that the two patterns are anticoincident on the left side of the hologram but coincident on the right side, and the situation then would be reversed. (Note: A comparison of Figures 10-16a and 10-16b will not disclose the small difference between positions S_1' , S_2' in Figure 10-16a and S_1' , S_3' in Figure 10-16b. Nevertheless, the two sets of positions are sufficiently different to interchange the coincident and anticoincident characteristics of the holoplate.)

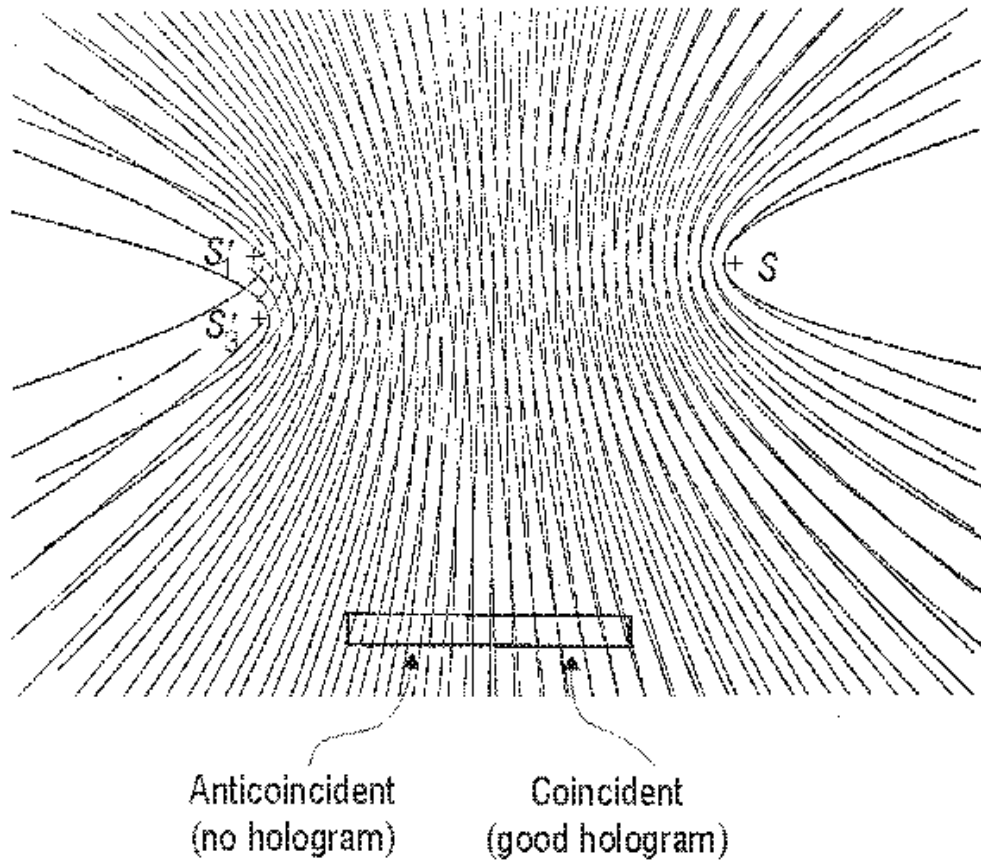


Figure 10-16b A double-exposure hologram of S' in two different locations. The two interference patterns are anticoincident at the left of the hologram but coincident at the right side.

Therefore, when a rigid object is slightly moved (displaced) between the two exposures, a set of straight black lines (fringes) will be superimposed on the image of the object. Each point on any given fringe will displace the same distance. On the other hand, if the object is deformed (such as a “live” plant having grown between exposures), complex curved fringes will be observed.

All points on a given fringe represent locations with the same displacement.

“**Time-averaged**” holographic interferometry is a single-exposure hologram of an object under normal mode vibration. The antinodal areas are moving, so the interference patterns are “smeared out.” The nodal areas have not moved; thus they appear bright. This renders vibration modes directly visible. (This technique has been used in the study of musical instruments.)

“**Real-time**” holographic interferometry involves making a hologram, processing it, relocating it in the position where it was made, and observing the virtual image superposed on the real object. If the object is moved or deformed (such as a growing object), the wave front of the image interferes with light from the real object, and an interference pattern can be observed in real time.

Holographic interferometry encompasses an entire discipline in mechanical engineering and is applied widely to solve myriad technical problems, mostly in the area called *nondestructive testing*.

Coherence Length (temporal coherence)

One of the basic techniques in making good holograms is to ensure that the optical path of the object and the reference beams are equalized well within the *coherence length* of the laser light. Beginning from the output of the laser, trace the total distance traveled by the reference beam to the hologate. Now do the same for the object beam. The difference in the two distances must not exceed the *coherence length*. So, what is this coherence length?

In general, lasers operating without internal etalons emit simultaneously more than one frequency (see Module 1-5, *Lasers*). For example, the low-cost helium-neon lasers emit typically two to three different frequencies simultaneously.

When a hologram is recorded by using a two-frequency laser, one can think of it as the sum of two holograms being made simultaneously, one at each frequency. The higher-frequency interference pattern is caused by light with a shorter wavelength, thus it has more interference orders over any given space. Figure 10-17 is the superposition (summation) of two independent sets of interference patterns, one caused by S_1 and S_1' of one frequency and the other caused by S_2 and S_2' of a slightly higher frequency.

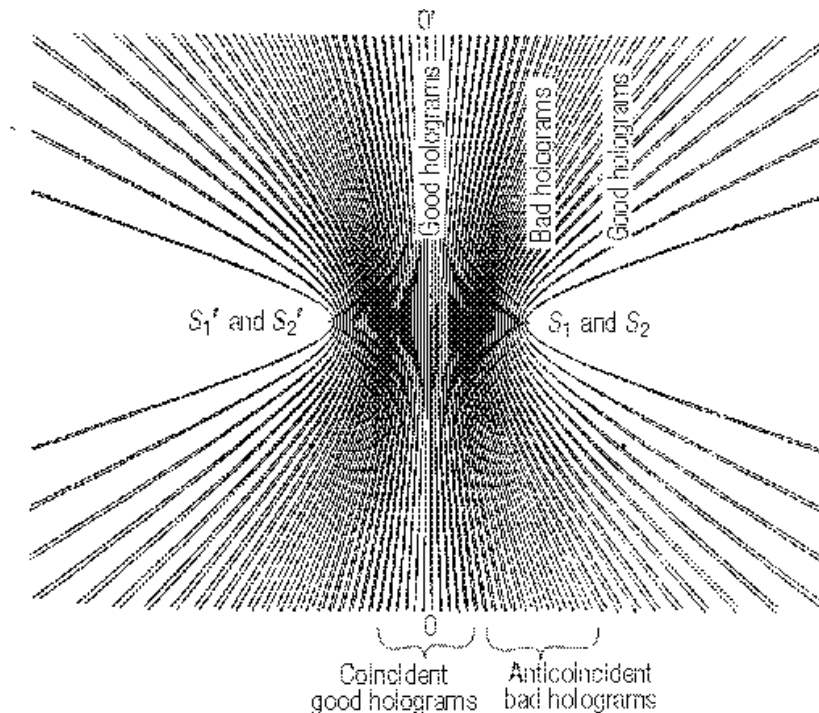


Figure 10-17 A superposition of two independent sets of interference patterns, each caused by light of slightly different wavelength from the other. The smudge-like area is caused by the anticoincidence of the two patterns; no hologram can be recorded there.

Near the zeroth order OO' in Figure 10-17 (the flat plane that is midway between the two interference point sources, the two sets of interference patterns coincide. Near this region, light of *any* color can produce distinct interference patterns. Lippmann photography is based on this fact. If a hologate is located in this area, a good hologram can be made. On the other hand, notice the two dark, smudge-like areas, one on each side of the zeroth order. This is caused by

the fact that the maxima of one pattern are located at or near the minima of the other pattern. If the holoplate is located in this region, the hologram will be very dim or not exist at all.

The *coherence length* of this two-frequency laser can be defined verbally as *the difference in distances travel by light from points S_1, S_2 and S_1', S_2' to the center of either dark area*. For a typical HeNe laser, this distance is about 30 cm.

Notice (Figure 10-17) that, if we increase the difference in the optical paths, the two patterns become coincident again.

For lasers with internal etalons or for highly stabilized diode lasers, the output has only one frequency and the coherence length is many meters. When using such lasers for making holograms, one does not need to equalize optical paths between reference and object beams.

Thin holograms

As is true with all “models,” the physical model for holography must break down at a limit (like the stick-and-ball model for molecules). Our limit is the “thin” hologram.

A hologram is considered “thin” when the separation between successive hyperboloidal surfaces exceeds the thickness of the recording medium. At this point, the model breaks down because there no longer is a set of hyperboloidal surfaces to be recorded. For example, embossed holograms (baseball cards and VISA/MC cards) are made by stamping a set of two-dimensional interference patterns on a sheet of plastic. These holograms cannot reproduce true color because there is no Bragg diffraction.

Then how does one explain the theory of a thin hologram?

A thin hologram is made by recording a two-dimensional interference pattern between a reference beam and light from the object on the surface of a recording medium (Figure 10-18). If the location of the holoplate is sufficiently far from S and S' , the two-dimensional interference pattern formed at the surface of the holoplate consists of *Young's double-slit* interference patterns (Module 1-4, *Basic Physical Optics*). The pattern consists of a set of straight dark and bright parallel lines whose spatial frequency depends on the distance of S from S' (slit separation) and the distance the hologram is from S and S' (screen distance).

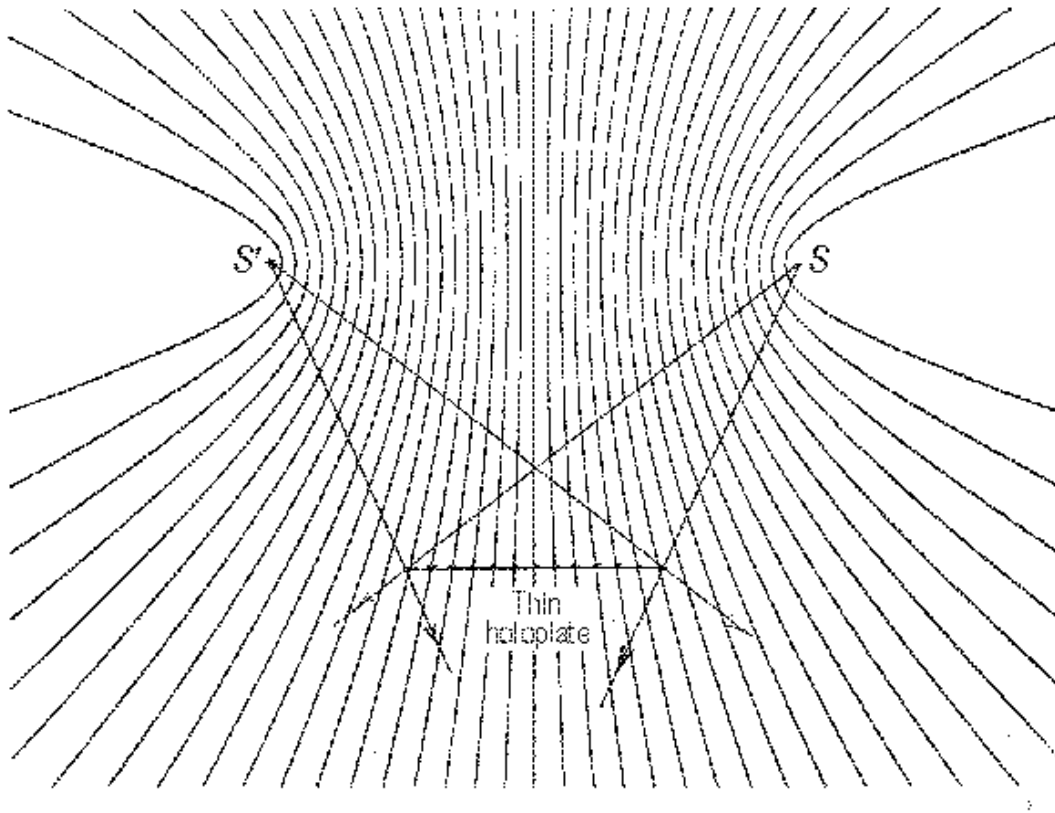


Figure 10-18 A thin hologram is made by recording a two-dimensional interference pattern on the surface of a recording medium. The result is a diffraction grating.

We learned previously (Module 1-4, *Basic Physical Optics*) also that a set of parallel dark and transparent lines is called a *diffraction grating*. When we are making a thin hologram, light from each point (S') on the object interferes with S and forms a two-dimensional diffraction-grating-like pattern on each small area of the hologram. Therefore, *each small area of a thin hologram is a summation of diffraction gratings formed by the interference of light from each point on the object with the reference beam*. The branch of mathematics used for quantitative study of holography is called *Fourier transformation*, and the formation of a hologram is a process called *Fourier synthesis*.

When the hologram is illuminated by S , each grating on each elementary area diffracts light to recreate the wave fronts of an object point (a process of *Fourier analysis*). If white light is used to illuminate this hologram, each different wavelength will be diffracted to a different angle and the image is smeared into a continuous spectrum. Thus, the transmission holograms discussed previously are best viewed with laser light.

In reality, most holograms are “quasi-thick” and “quasi-thin,” requiring a combination of physical explanations.

Laboratory Practices

Introduction

In this section, laboratory exercises will be arranged so that we start with simple procedures using simple equipment. The low cost of equipment makes it possible for many of the following exercises to be performed as “homework.”

All the experiments require the use of a laser and chemicals for processing the holograms. Section I, “Diode laser holography,” uses a class IIIa diode laser without the collimating lens, rendering it useless as a “pointer.” This allows the work to be performed by students at home. When higher-power lasers are used, in section II, “Advanced holography,” supervision by a qualified instructor is required.

Always observe all safety rules concerning lasers and chemicals.

Generally, the developer and bleach solutions are mixed by the instructor. Since the photochemistry of holography is an ongoing research, it will change as improvements are found. Thus, no particular regime is discussed here. Use according to the detailed instructions that accompany each processing kit provided by the manufacturer.

Similarly, the holographic plate or film used will change with time. Use them in accordance with the instructions of the supplier. The exposure time and the appropriate processing scheme are also provided.

Equipment and facilities

Holograms are made in darkened areas free from drafts, vibration, and noise. Because of the relatively low sensitivity of the recording material, sufficient light is allowed so that one can see comfortably after dark adaptation. To achieve this, use a 25-watt green light bulb in a lamp. Place the lamp under the table, cover it with aluminum foil to adjust the light, and direct it toward the floor. Do not allow direct light to shine on the holography system or on the developing station.

If the room has windows, cover them with black plastic sheets. Enough light can leak through to allow minimum vision after dark adaptation. In case of doubt, leave a holographic plate on a table and expose it to the ambient light for ten minutes. Develop it. If it turns dark, there is too much light.

Flowing tap water is desirable but not necessary. A large tray of clean water can be used to rinse the developed hologram. White trays are desirable because they allow continual inspection. An alternative is to use glass trays resting on white paper.

Make sure all fire codes are observed.

I. Diode laser holography

Certain class IIIa diode lasers sold as “pointers” are found to have high-frequency stability and thus long coherence length after an initial warm-up of a few minutes. With the collimating lens removed, the laser light spreads directly from the laser with a highly eccentric elliptical profile. Since the beam does not encounter other optical elements, it is completely “clean.” This allows it to be used to make many types of holograms without additional optical components.

These experiments are to be performed on top of a sturdy lab table or kitchen counter or on the floor. Support a thick 50-cm \times 100-cm wooden board (or optical table) on top of four “lazy balls” (rubber balls that don’t bounce). Put washers under each ball so that they will not roll.

A. Reflection hologram

Equipment requirement: Darkened room with green safe-light, sturdy table or counter, optical table supported by “lazy balls,” mounted diode laser system, object on platform with three-point support, shutter, processing trays with chemicals, and holographic plates.

Figure 10-15—shown earlier—indicates the setup for making a “one-beam reflection hologram,” sometimes called a Lippmann (Nobel Prize in physics, 1908) or Denisyuk hologram.

Procedure

- A. Choose a solid object that looks bright when illuminated with laser light and whose size is not bigger than the hologram to be made. Mount (hot glue) it on a small platform made of wood or sheet metal (15 cm \times 15 cm) with three round-head short screws underneath (to prevent rocking). Mount the laser on a stand about 25 cm high and direct the light down at 45° at the object, with the light spreading horizontally. The distance between the laser and the object is about 40 cm. Now turn on the safe light and turn off the room light.
- B. After the laser has been warmed up for at least five minutes, block the light from reaching the object using a self-standing black cardboard. (We will call this the shutter.)
- C. Lean a holoplate directly on the object, with the sticky side touching it. Wait at least 10 seconds.
- D. Lift the shutter, *but still blocking the light*, for 2 seconds, to allow any vibration to subside. Then lift the shutter away completely to allow the light to pass through the holoplate. The exposure is usually about 5 seconds. (Consult the instructions that accompany the plates.) Then block the light again.
- E. Develop the hologram according to instructions from the manufacturer.

After the hologram is dried, view it with a spot light such as a pen light, projector, or direct sunlight. Optional: Spray paint the sticky side (emulsion side) with a flat (or “antique”) black paint to provide a darker background and greatly improve the visibility of the image.

B. Transmission holograms

1. Without a mirror

Equipment requirement: Same as for the “reflection hologram” in section A. above. In addition, a stand-alone plate holder is needed. Make one exactly the same way as the object platform described above. Instead of the object, install two long (12 cm) screws on top with a separation less than the width of the holoplate to be used. Paint the screws a diffused black color.

Procedure

- A. Set up the system as shown in Figure 10-19. The diode laser is mounted 5 cm above the optical table with the beam spreading horizontally. One side of the beam illuminates the object or objects, and the other side serves as reference beam.

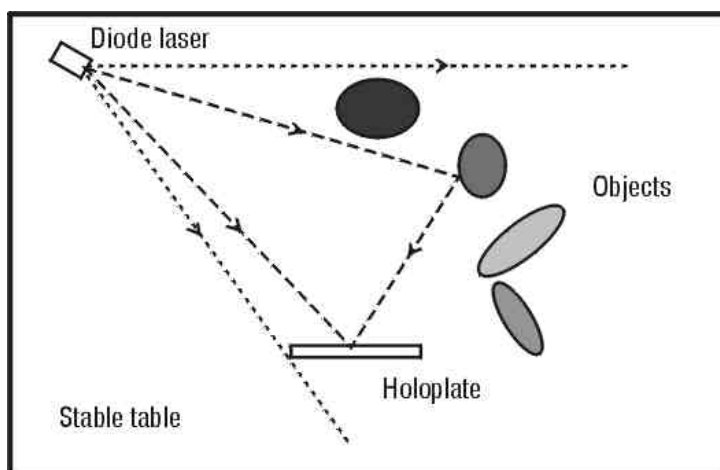


Figure 10-19 The simplest configuration for making a transmission hologram

- B. Block the beam with the shutter, turn off the room light, and, on the stand-alone plate holder, lean a holoplate vertically against the black screws with the sticky side facing the object(s). Wait 10 seconds.
- C. Lift the shutter and expose for about 30 seconds. Note: If there is a draft across your system, the long exposure time of 30 seconds requires you to put a large box over the entire system during the exposure.
- D. Develop and dry as before.
- E. This hologram must be viewed with laser light. To do so, lean the finished hologram back on the black screws the same way as during exposure. Cover or remove the objects and look through the hologram toward the location of the objects. A *virtual image* can be seen as if the object is still there.
- F. To observe the *real image*:
 - Relocate the finished hologram in the position where it was exposed.

- Remove the object and, in its place, position a vertical white screen (cardboard) facing the hologram.
- Darken the room and direct a collimated laser beam *through* the center of the hologram in a direction that is 180° from the original reference beam, i.e., back toward the location of the diode laser used for making the hologram.

All light paths are now reversed and a two-dimensional image is projected onto the screen. Move the laser beam to different locations of the hologram and observe the changing perspectives of the image.

2. Transmission hologram with one mirror

Note that the objects in the foregoing transmission hologram are always illuminated from the side. To get more frontal lighting, we need to add one flat, front-surface mirror.

Equipment requirement: Same as above, plus one front-surface mirror. Mount this mirror in a vertical position by hot-gluing the back side (the glass side) to a block of metal or wood, with the bottom edge raised to the same height as the bases for the object and the plate holder.

Procedure

The procedure is the same as for section B.1 (transmission holograms without a mirror), but using the setup as shown in Figure 10-20. Note that a baffle in the form of a black cardboard is needed to block the laser light from exposing the holoplate from the back side. To project the real image onto a screen, set the finished hologram back onto the plate holder and direct a laser pointer backward through the hologram, onto the mirror so that the beam hits the diode laser. On a screen located at the position of the object, the real image is formed.

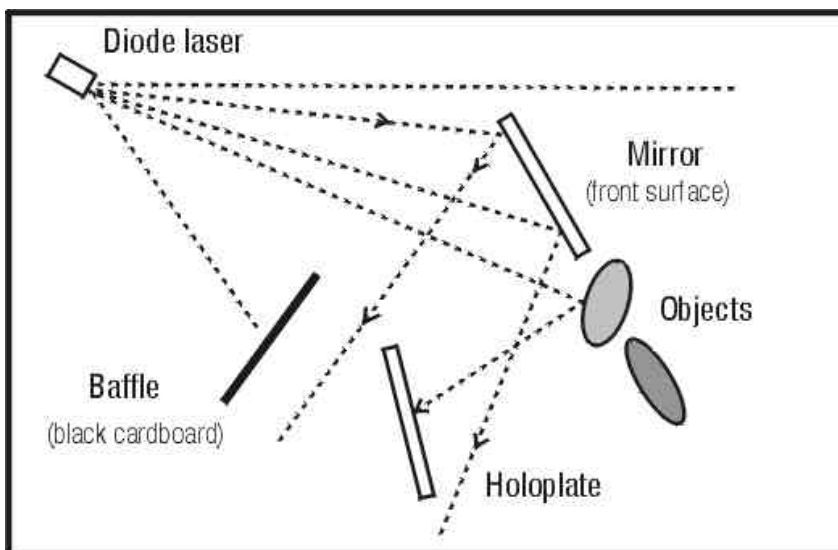


Figure 10-20 With the addition of one front-surface mirror, the hologram can be made facing the objects and the objects are better illuminated.

3. Two-channel transmission hologram

Use the same procedure as for the “transmission hologram with one mirror,” except now make the exposure time one-half as long. Pick up the holoplate and rotate it upside down (with emulsion or sticky side still facing the object) and place it back on the plate holder. Replace Object 1 with Object 2. Expose again one-half the full time. Process as before.

In viewing the virtual or real image, notice that, depending on which side is up, a correspondingly different image is observed.

4. Diffraction grating

Set up the experiment according to the layout shown in Figure 10-21. The plane of the mirror should make a 90° angle with the plane of the holoplate. Notice that no object is used in this experiment.

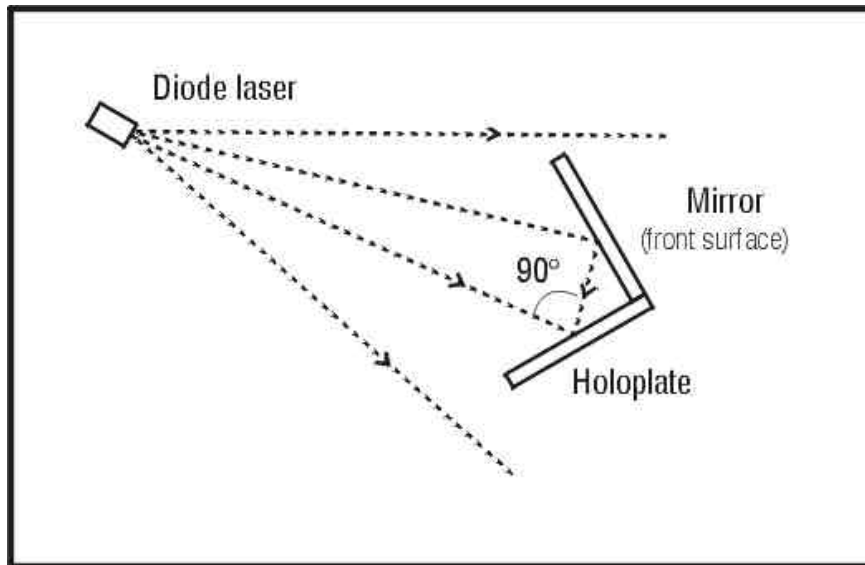


Figure 10-21 Making a hologram of light reflected from a mirror results in a high-dispersion diffraction grating.

Here the “object” is part of the beam from the laser that is redirected by the mirror. This configuration is the same as shown in Figure 10-6, in which both the reference and object beams are point sources.

Use the same procedure as before but with a shorter exposure time (approximately 75% as much) and process similarly.

Project the real image of the finished hologram onto a screen at the location of the mirror. Is there any difference between a real and a virtual image in this case?

If you see more than one spot, the extra ones are caused by internal reflections inside the holoplate. To avoid these reflections, an anti-halation backing of the holoplate is required. This is done by painting on the glass side of the holoplate, before exposure, with a washable blue or black water-color paint. This absorbs the light as it arrives at the back surface during exposure.

This hologram is in effect a high-dispersion diffraction grating. Shine a beam of white light from a slide projector through the hologram and observe the spectrum on a screen. Use other sources such as mercury and sodium lights from the street during the night.

5. Additional project

Design a system using this holographic grating to observe the Fraunhofer lines from the sun. It will show which elements exist in the sun!

II. Advanced holography

The preceding experiments are fundamental. They use simple equipment to demonstrate the major principles of holography. However, they have many limitations. For example:

- The intensity ratio between the reference and object beam cannot be controlled. Thus the quality of the hologram cannot be optimized.
- The object is always illuminated with a single point source from a fixed direction, thereby casting shadows that cannot be controlled.
- The location of the image is always behind the plate.
- A laser is needed to observe the image formed by transmission holograms.

To make holograms with none of the above restrictions, the following **additional equipment** is needed:

- A higher-power laser that operates in a single transverse mode. It's even better if it operates in a single axial mode. A 10- to 30-milliwatt HeNe laser is recommended.
Observe all laser safety rules !!
- A power meter with a sensitivity range of 1 microwatt to 1 watt
- A large (4 feet \times 8 feet is typical) isolation table with adjustable front-surface mirrors (4); lens with the largest aperture and shortest positive focal length (1); variable beam splitters (2); spatial filters with 10X objective and 25-micron pinholes (3); 4 \times 5-inch ground glass plate (1); plate holder (1); and hardware for supporting all the above components
- *Alternative, low-cost system:* Build a sandbox (3 feet \times 4 feet \times 10 inches) with thick plywood and fill it with washed silica sand (the kind sold for sandblasting). Substitute spatial filters with small, double-concave lenses and concave mirrors. Mount (glue) all optical elements on top of 2.5 inch diameter PVC pipes (which allows x - y - z position adjustments when stuck into the sand). Use film instead of plates and sandwich it between large glass plates with strong paper clamps. (Just stick the sandwich into the sand.) Support the sandbox by a dozen "lazy balls" and put the system on a rolling table. The cost of this system is an order of magnitude less than the commercial system and is more mobile and versatile for the purpose of learning.

A. Split-beam transmission hologram

The following symbols are used in the diagrams for the remaining experiments:

	Front surface mirror		Negative Lens
	Beam splitter		Ground glass
	Positive Lens		Pinhole
	Laser		Hologram, or film

Note: A lens followed by a pinhole is a spatial filter.

Figure 10-22 is the layout for making a highest-quality transmission hologram. The procedure is general and is applicable to all of the remaining experiments.

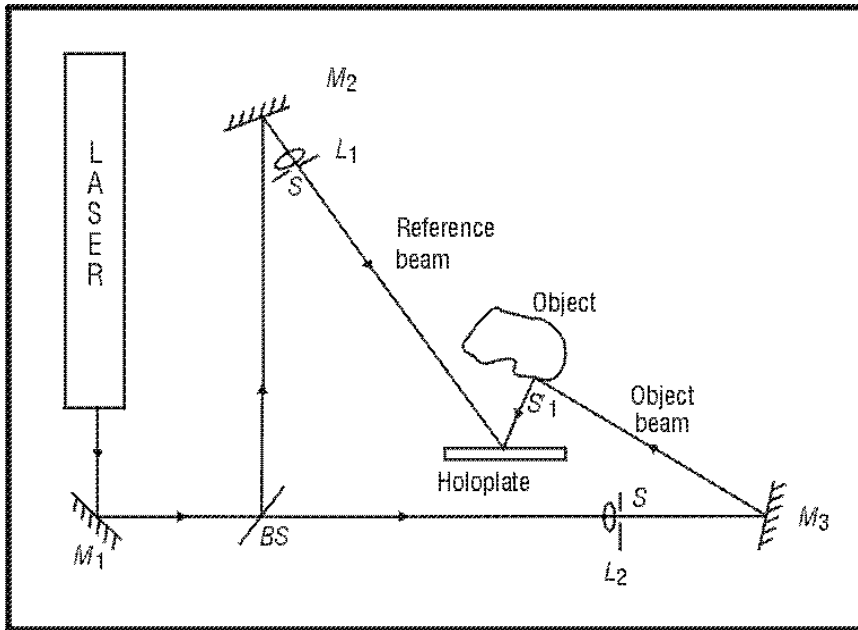


Figure 10-22 A general configuration for making the highest quality transmission holograms

- Lay out the components as shown in Figure 10-22 except for the two spatial filters L_1, S and L_2, S (or meniscus double-concave lenses).
- Equalize the beam paths by using a cord. Start from the beam splitter BS , and measure the total distance from BS to M_2 and on to H . Now measure the distance from BS to M_3 , on to the center of the object O and on to H . Equalize the paths within 2 or 3 cm by moving mirror M_2 .
- Expand the two beams by positioning the spatial filters (lenses) as shown. The reference beam should cover the holoplate (here substituted for by a white card during alignment). The object beam should light up the object.

- D. Baffling: From the position of the holoplate, carefully observe light scattered from anywhere other than from the object and the reference beam. Block all the unwanted light using black cardboard.
- E. Measure the intensity ratio of the two beams incident on the holoplate with the power meter by positioning the meter at the location of the holoplate. Block the light from the object beam and read the intensity of the reference; then block the reference beam and read the intensity of the light beam from the object. Adjust the intensity ratio of reference beam to object beam reading to about 4:1 to 8:1 by two methods: (1) use a variable beam splitter; (2) move the beam-expanding lenses appropriately along the beam paths.
- F. Determine the exposure time.
- G. Now expose and develop the hologram.

If “soft” lighting of the object is desired, a ground glass can be placed between the object and mirror M_3 . Carefully baffle any light from the ground glass directly to H .

B. Dual-object beam transmission hologram

Figure 10-23 shows a layout for illuminating the object with two beams. This allows artistic lighting through the addition of a beam splitter, spatial filter, and mirror. Soft lighting with ground glass(es) is also possible.

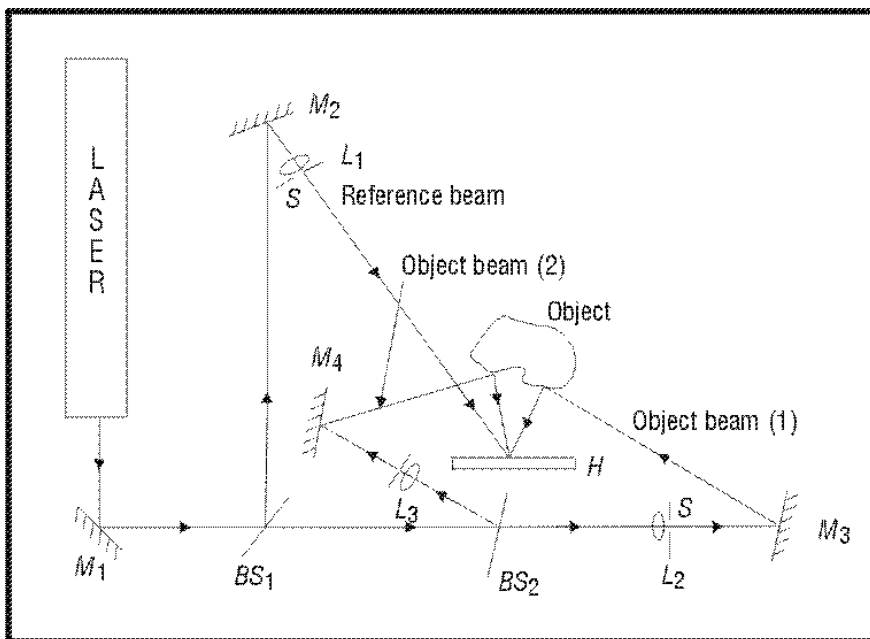


Figure 10-23 *The object is illuminated from two independent beams, allowing more artistic lighting.*

The beam path of the added beam (object beam 2) must be equalized, starting from the beam splitter BS_1 . Then proceed with instructions given in II.A. above.

C. Focused-image reflection hologram

Figure 10-24 shows a layout for making a reflection hologram in which the image appears in the plane of the hologram. Here the large lens with a short focal length is used to image the object onto the plane of the hologram. The object and the hologate are located at a distance equal to $2f$ on the opposite sides of the lens. This allows the image to be the same size as the object.

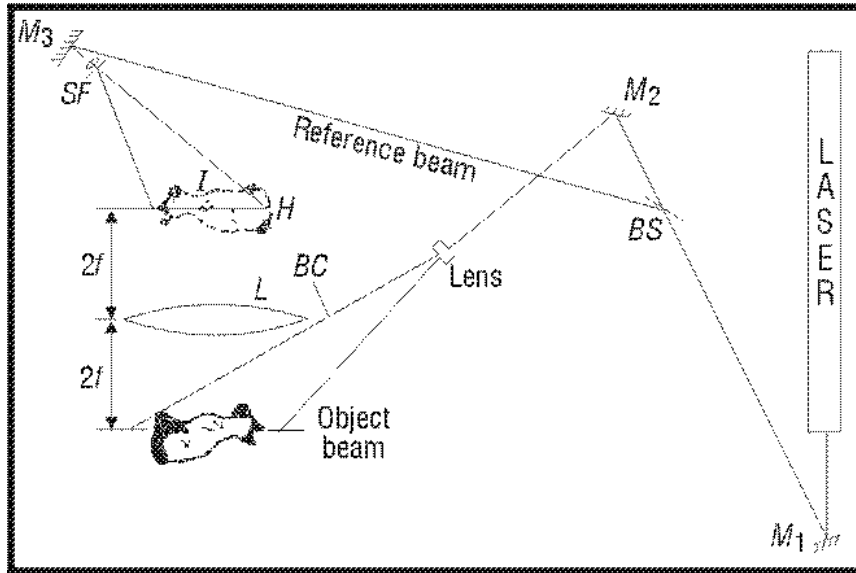


Figure 10-24 A configuration for making a focused image reflection hologram

During alignment, use a white card to find the real image of the object and place the plate holder there. As is true for making reflection holograms in general, a good beam ratio is 1:1.

Notice that in this experiment we are making a photograph and a hologram at the same time!

Problem Exercises/Questions

1. What is the most basic difference in the recording of reflection holograms and transmission holograms?
2. When a transmission hologram is broken into many pieces, each piece can reconstruct the image of an entire view of the object. Why?
3. When a reflection hologram is broken into many pieces, each piece cannot reconstruct the image of an entire view of the object. Why?
4. It is generally not possible to use commonly available photographic film to record holograms. Design a very particular hologram that can be made using these films.
5. What type of hologram, even if it is thinner than a wavelength of light, can record and reproduce a completely three-dimensional image? Explain.

6. Can holograms be made using one laser for the reference beam and another laser for the object beam? Why?
7. If you have to make a hologram using low-power diode lasers near a location that has trains going by all the time, what type of hologram should you try to make to optimize your chance of success?
8. Why can we use the sun to reconstruct the image of a reflection hologram but not of a transmission hologram?
9. Dennis Gabor discovered holography in 1947 before the laser was invented. How do you think he made the first hologram?
10. Explain how a reflection hologram selects the color from the light used to illuminate it.
11. You have made a reflection hologram using red laser light. Why is the image generally not red, but yellowish or greenish?
12. How is it possible to make a hologram with more than one scene that can be viewed one at a time through the full aperture of the hologram?
13. Why do we bleach the holograms after development?
14. Explain how a double-exposure hologram of an object that changes microscopically between exposures reveals the nature of the change.
15. When making holograms, we try to equalize the optical paths traveled by the reference and object beams. Why? Under what condition is this procedure not necessary?

Bibliography

Rossing, Thomas D., and Christopher J. Chiaverina. *Light Science, Physics and the Visual Arts*. New York: Springer-Verlag, Inc., 1999.

Saxby, Graham, *Practical Holography*, 3rd edition. Prentice-Hall, Inc., 1996.

Jeong, Tung H. *Laser Holography—Experiments You Can Do*. Lake Forest, Illinois, Thomas Alva Edison Foundation, Integraf, 1987.

Vest, Charles M. *Holographic Interferometry*. New York: John Wiley & Sons, 1979.

Bjelkhagen, Hans I. *Silver-Halide Recording Materials for Holography and Their Processing*, 2nd edition. New York: Springer-Verlag, 1996.

Pedrotti, Leno S., and Frank L. Pedrotti, *Introduction to Optics*, 2nd edition. Prentice-Hall, Inc., 1993.