Holography

11

Looking at holographic images is exciting! Some appear to float in space; some appear in full color; some change color as you move your head; some even show subjects that move. No wonder that artists are using holograms to create a new art form. In this chapter we will explore the physics of holography and try to learn what makes holographic images so unusual.

11.1 What Is a Hologram?

With photography, a recording of an object is made in the form of a two-dimensional picture on light-sensitive film. A lens, or a system of lenses, is used to capture the variation in brightness of the object, which in turn produces a corresponding variation in exposure on the film.

Unlike making a photograph, creating a hologram does not require a lens. There is no reproduction of the object on film. Instead, the film is used to record the distribution of light energy in space. As a result, without suitable lighting, a hologram reveals nothing of the visual information contained within. However, with proper illumination, the hologram's image will appear, as if by magic, with virtually all the optical properties of the object itself.

The basic technique used to create a hologram was developed by Dennis Gabor in 1947 primarily as a means for improving electron microscopy, and it eventually won him the Nobel Prize in Physics. Gabor's wavefront reconstruction process led to recorded patterns that he called *holograms* from the Greek word *holos*, meaning "whole." His process went more or less unused, however, until after the invention of the laser in 1960, when Emmett Leith and Juris Upatnieks (United States) and Yuri Denisyuk (Russia) adapted Gabor's technique to produce optical holograms.

A hologram is a two-dimensional recording of an interference pattern capable of producing a three-dimensional image. It does that by recording the whole wave field, including both the *phase* and *magnitude* of the light waves reflected from an

T. D. Rossing and C. J. Chiaverina, *Light Science*,
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object. The phase information is converted into intensity information (which can be recorded on film) by using a *reference beam* of *coherent light*, monochromatic light in which electromagnetic waves maintain a fixed phase relationship with each other over time. Light from sources such as the Sun, a candle, or a light bulb does not have these properties; laser light does.

The most striking feature of a hologram is the three-dimensional image that it forms. A hologram, such as the one of physicist Gabor in Fig. 11.1, appears to be a window through which a three-dimensional, lifelike image is seen. Moving the head from side to side or up and down allows the viewer to look around the object.

Furthermore, if a hologram is broken into small pieces, the entire image can be seen through any piece, although the viewing window becomes much smaller. This is because a hologram records information about the whole scene in each small piece of the film. As Fig. 11.2 indicates, each piece of the broken hologram provides a view of the recorded object from a different perspective.

There are two basic types of holograms: reflection and transmission. A *reflection hologram* can be viewed with a spotlight or a point light source (the Sun works particularly well) as if it were a three-dimensional painting. A *transmission hologram* is illuminated from behind by a monochromatic light source (laser light works well) . The way in which interference patterns are formed in the photographic emulsion in these two cases is shown in Fig. 11.3. Holograms can provide either real or virtual images.

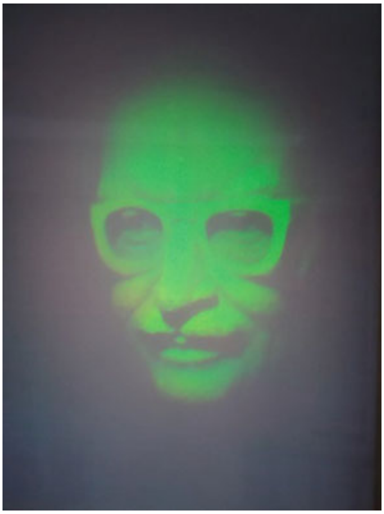


Fig. 11.1 A hologram of Dennis Gabor, the inventor of holography (Courtesy of The Jonathan Ross Hologram Collection)

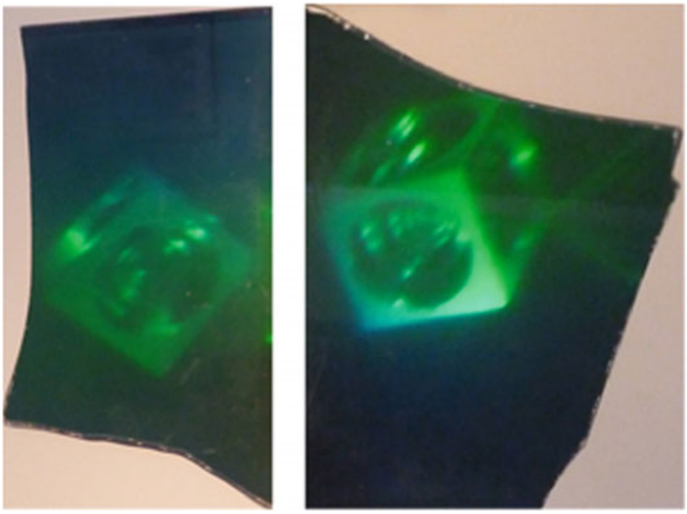


Fig. 11.2 Photograph of two different sections of a broken hologram. Each piece offers a view of the object from a different angle (Epzcaw (https://commons.wikimedia.org/wiki/File:Broken_hologram.jpg), “Broken hologram”, https://creativecommons.org/licenses/by-sa/3.0/legalcode)

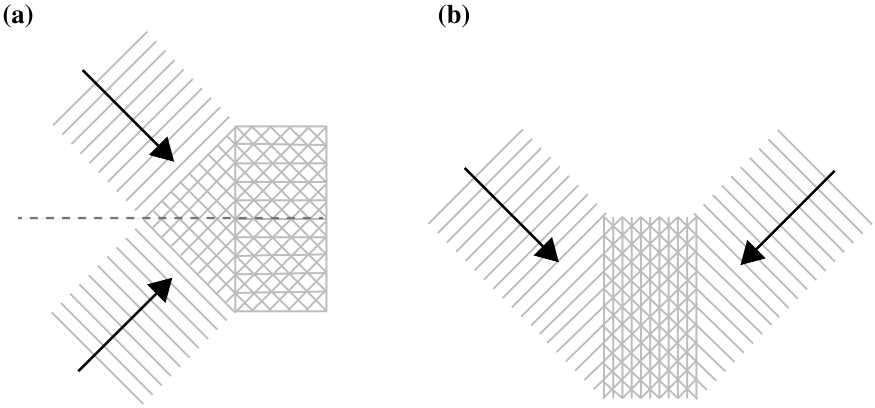


Fig. 11.3 **a** The interference of two plane waves traveling toward the same side to create a transmission hologram; **b** the interference of two plane waves traveling toward opposite sides to create a reflection hologram

In addition to basic transmission and reflection holograms, there are many special types, such as: volume holograms, “rainbow” holograms, true color holograms, multiplex holograms, embossed holograms, integrams, motion holograms, and holographic interferograms. Digital signal processing has led to TV holography, in which holograms are created electronically in digital computers.

Virtual and Real Images

When a hologram is illuminated by a replica of either of the two original beams alone, both of the original beams will emerge. Thus, if you place the hologram back in the original reference beam, both this beam and a replica of the original object beam will emerge. If you look along the reconstructed object beam, you see a replica of the object; because it appears that the light had originated from the object, this image is called a *virtual image*. In contrast to the virtual image, an image that light has actually passed through is called a *real image*; it can be projected on a screen.

When a hologram is illuminated in a backward direction using a reference beam in reverse, a real image is produced in the location of the original object. This image has some unusual properties. Its perspective is reversed; parts of the image that should be at the rear appear at the front (the image of a ball, for example, looks like a hollow cup and vice versa). Moreover, parts in the image that appear to be in the rear cast shadows on parts that appear to be in front. The image is thus called a *pseudoscopic image*, in contrast to an *orthoscopic image* having normal perspective. A hologram can be made to produce both an orthoscopic and a pseudoscopic image by turning it through 180 degrees on a horizontal axis (“flipping” it).

11.2 Transmission Holograms

The basic arrangement for recording and viewing a transmission hologram is shown in Fig. 11.4. The object and a nearby photographic plate are both illuminated by laser light. The portion of the laser light that goes directly to the plate is called the *reference beam R*, while the portion that illuminates the object is called the *object beam O*. The film records the interference pattern between the light scattered by the object *S* and the reference beam *R*; this record is the hologram of the object. To view the finished hologram, place it back where it was made, look through it toward the object, and remove the object.

A slightly better way to record a hologram is shown in Fig. 11.5a. A plane mirror *M* in the laser beam directs some of the laser light to the photographic plate (reference beam *R*) while the balance of the light illuminates the object (object beam *O*) . The main advantage is better lighting of the side of the object facing the photographic plate. The holographic image can be viewed by replacing the developed plate in the reference beam and blocking off the object beam as shown in Fig. 11.5b; the image will appear in the same place as the original object.

Two-Beam Transmission Holograms

Both the setups for recording transmission holograms shown in Figs. 11.3a and 11.4 might be called one-beam systems because the same beam of laser light, spread out by a lens, serves as the reference beam and the object beam. It is difficult to change the relative intensities of the reference and object beam, which is a

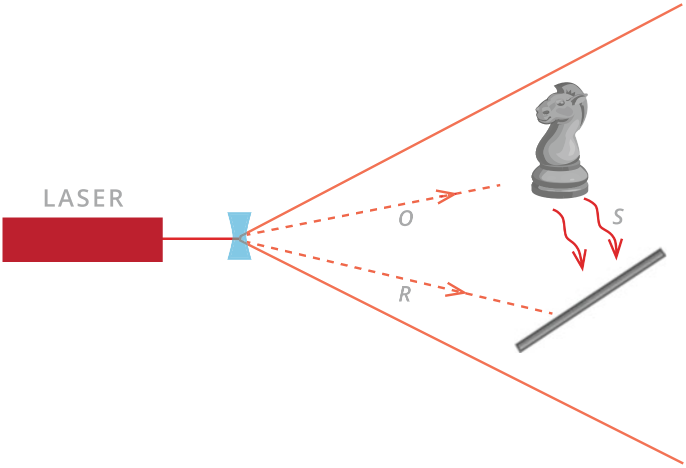


Fig. 11.4 Basic setup for recording a transmission hologram

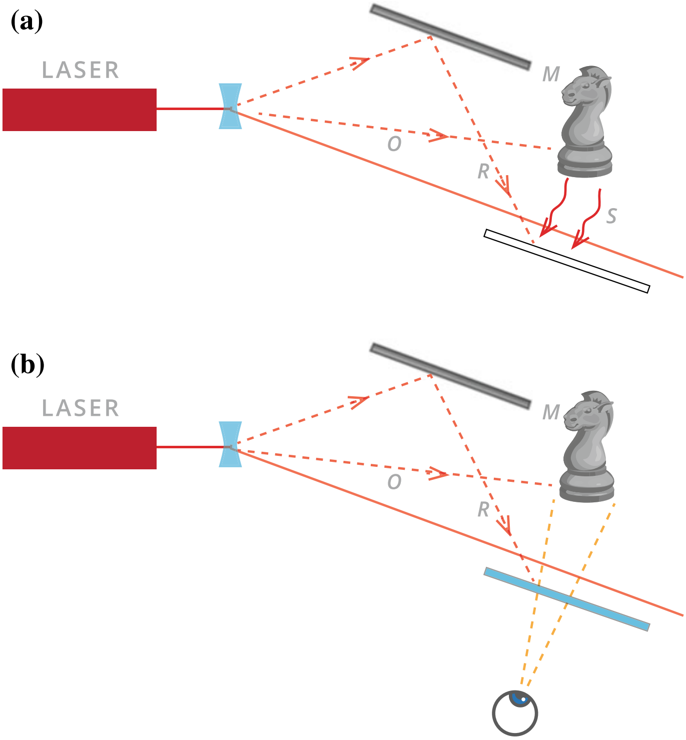


Fig. 11.5 **a** Another setup with a mirror used to record a transmission hologram; **b** viewing the holographic image

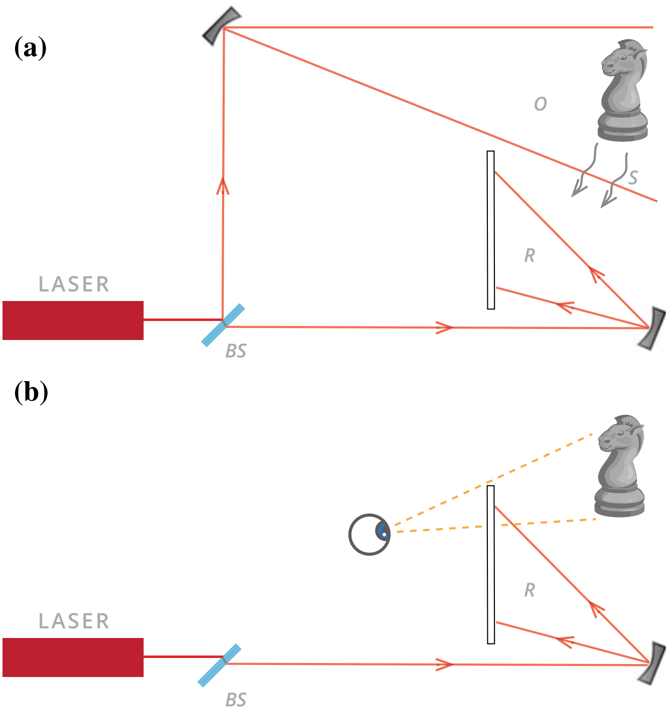


Fig. 11.6 **a** Two-beam system with a beam-splitting mirror. **b** The image can be viewed with the reference beam

disadvantage if the object changes from light to dark, for example. For this and other reasons, a beam-splitting mirror is often used to produce independent reference and object beams, as shown in Fig. 11.6a. Since the amount of light transmitted and reflected by the beam splitter can be adjusted, the relative intensities of the reference and object beams can be optimized. As Fig. 11.6b indicates, the image can be viewed with the reference beam.

11.3 Reflection Holograms

The simplest type of reflection hologram is the single-beam or *Denisyuk hologram* in which the beam falls on the emulsion from one side, acting as the reference beam, and passes through the emulsion to be reflected back by the subject matter on the other side to form the object beam, as shown in Fig. 11.7. The fringes formed are more or less parallel to the surface of the emulsion, spaced a half-wavelength apart, so that *Bragg reflection* (see below) controls the image formation. Thus, the image can be viewed with white light, and the image appears to have a certain color, which may not be that of the original laser beam.

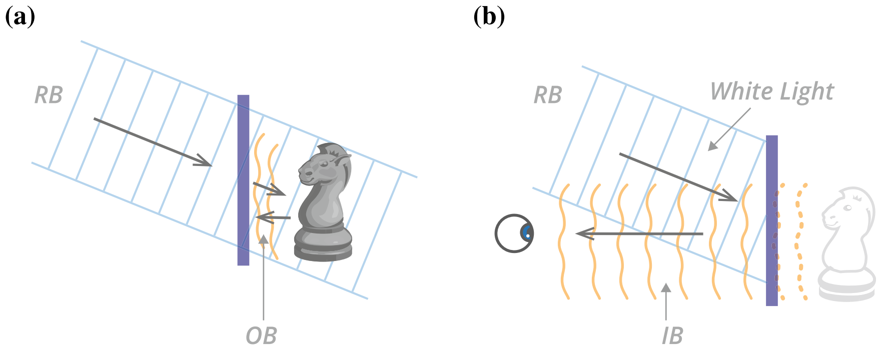


Fig. 11.7 Arrangement for single-beam reflection hologram. The reference beam RB passes through the emulsion and illuminates the object to form the object beam OB. The hologram is replayed by a reconstruction beam RB on the same side as the viewer

Bragg Reflection

In a single-beam (Denisyuk) reflection hologram, the reference beam and the object beams come from opposite directions and meet in the emulsion. There they interfere (or set up standing waves) so that, after processing, planes of varying absorption (or refractive index) occur in the emulsion. During reconstruction these planes act as weak mirrors, each partially reflecting the light beam. When these planes are a half-wavelength apart, the partial reflections add up, and the reflected beam is strong. Since the distance the light travels between planes depends on the angle of incidence, each color of light will have its maximum at a slightly different angle.

The relationship between the wavelength λ, the distance between planes d, and the angle θ of maximum light intensity is given by Bragg's law: $2d \sin \theta = m\lambda$. This law was first derived by Nobel laureate William L. Bragg to describe the behavior of X-rays in a crystal. (In a crystal, the atoms are arranged in planes that diffract the X-rays so that reflection occurs.) Bragg reflection allows white light to be used for image reconstruction from a reflection hologram. As the hologram is tipped so that the angle of incidence changes, the color of the reconstructed image also changes.

Bragg reflection also explains why the virtual image in a transmission hologram is brighter than the real image unless the hologram is "flipped" (see Sect. 11.1).

11.4 Transfer Holograms

A hologram can record anything that can be seen under laser light, including the image produced by another hologram. A *transfer hologram* uses the real image from another hologram as its object. The image from the first hologram can be situated behind or in front of the new hologram, which makes it possible to create very dramatic effects. To make a hologram of the real image, the master hologram is flipped, a second holographic emulsion is placed in the plane of the real image, and a suitable reference beam is applied. The final image can be made brighter by masking down the master of a reflection transfer hologram so that it is narrower in a vertical direction.

Rainbow (Slit-Transfer) Holograms

In 1968, Stephen Benton showed that the horizontal parallax in a hologram can be eliminated by making a transfer hologram in which the master is masked by a narrow horizontal slit. (Since binocular vision operates in a horizontal plane, the vertical parallax in a holographic image is not very important.) This led to a *slit-transfer* or *rainbow hologram* in which a change of viewpoint in a vertical direction results in a change in image hue but not in image perspective.

An arrangement for making and viewing a rainbow hologram is shown in Fig. 11.8. The master H_1 (a) is masked off to a narrow horizontal slit. This produces an image hologram H_2 in which the vertical information is replaced by a "diffraction grating" produced by interference between the image beam IB and the reference beam RB. When H_2 is flipped (b), the image of the slit is projected close to the eye of the viewer, and when H_2 is illuminated with white light, the image of the slit varies in its position according to the wavelength. The viewer sees the image in a spectral hue that depends on the height of the viewpoint.

A viewer moving up or down in front of a rainbow hologram sees changing spectral colors rather than different vertical perspectives. The holograms used on credit cards, paper currencies, and other documents to prevent forgery are examples of rainbow holograms. The rainbow hologram shown in Fig. 11.9 can be found on a 50 euro note.

Rainbow holograms can be produced using inkjet printers. A team of scientists from ITMO University in Saint Petersburg have developed a colorless ink made from a form of titanium dioxide that can be loaded into an inkjet printer. When deposited on specially treated paper, rainbow holograms of virtually any size can be produced in a matter of minutes, a process that normally requires hours if not days.

Perhaps one of the most unusual uses of rainbow holograms can be found on chocolate products. Morphotonix, a Swiss company located in Lausanne, has devised a way to create microstructures on the surface of chocolate (Fig. 11.10a). It

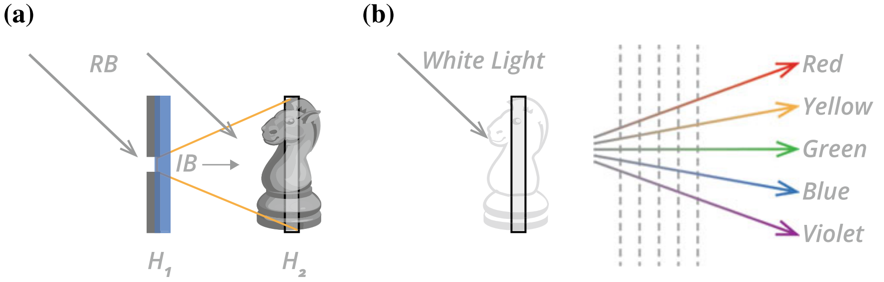


Fig. 11.8 **a** Making a rainbow hologram by masking the master H_1 off to a narrow slit; **b** viewing a rainbow hologram in white light

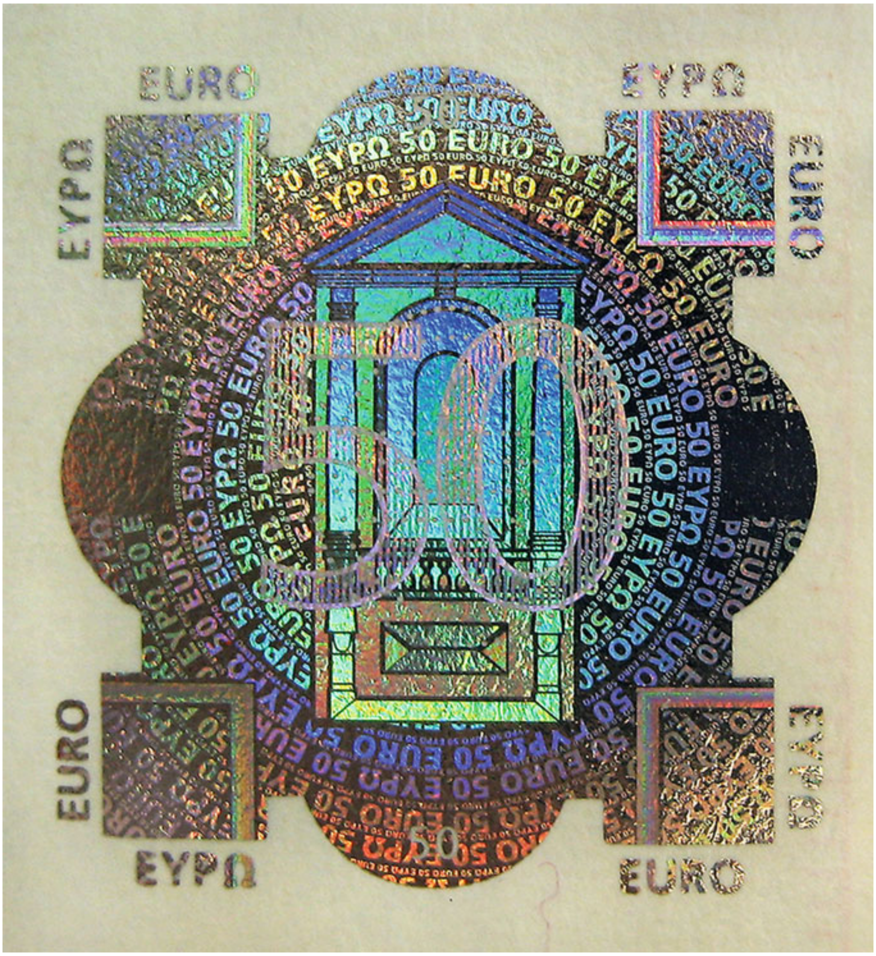


Fig. 11.9 A rainbow hologram on a 50 euro note (Heike Löchel (https://commons.wikimedia.org/wiki/File:Hologram.jpg), "Hologram", https://creativecommons.org/licenses/by-sa/3.0/legalcode)

is these microstructures that diffract light, producing the holographic effect. They first etch microstructures into a metal master mold, which they then use to make the plastic molds for shaping the chocolate. The final step involves injecting liquid chocolate into the plastic mold. The resulting product is a delicious edible hologram (Fig. 11.10b).

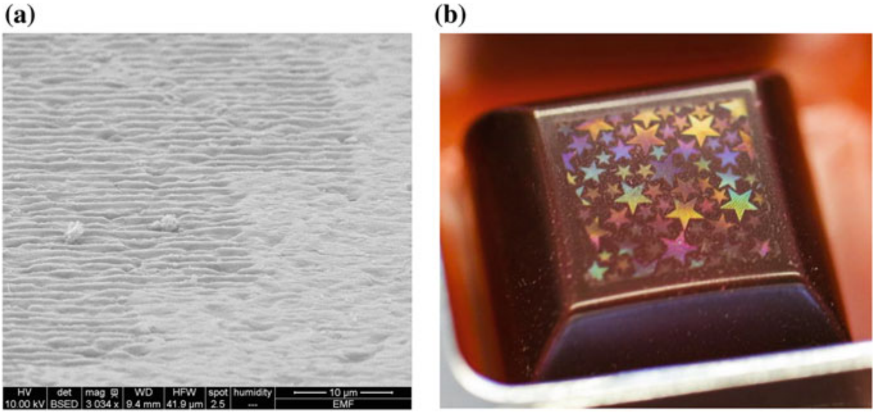


Fig. 11.10 **a** A scanning electron microscope image of the microstructures on the surface of a piece of chocolate. **b** A piece of Morphotonix's holographic chocolate (Courtesy of Morphotonix)

11.5 Phase Holograms

A hologram developed and fixed using conventional photographic processing methods is called an *absorption* or *amplitude hologram* because the recorded fringes modulate the amplitude of the transmitted beam. Viewed under a microscope, the developed silver grains have the appearance of opaque black mopheads. They absorb most of the light that falls on them and reflect only 3 percent or less.

However, if the hologram is *bleached*, the silver particles are changed back into transparent silver bromide and the reconstructed image becomes much brighter. The refractive index of silver bromide is very high, and so the fringes form a multilayered interference mirror. The bleached hologram is called a *phase hologram* because the recorded fringes now modulate the phase of the transmitted beam during image reconstruction.

11.6 Color Holograms

An important goal in holography has been to make holograms in full natural color. Although various special techniques have allowed for the production of holograms exhibiting several different colors, in most cases the colors in these holograms are not the original colors of the object. Such holograms, often referred to as *pseudocolor* or *multicolor holograms*, give an impression of true color, although the recordings could well have been made from objects having completely different colors.

Fig. 11.11 True color (panchromatic) reflection hologram of Chinese vase (Hologram courtesy of Hans Bjelkhagen)

Making a true color hologram, such as the one shown in Fig. 11.11, generally requires three beams of monochromatic light, and these beams need to follow precisely the same path. This can be accomplished by using a laser with several spectral lines and a tunable cavity, but it is more commonly done with three different lasers. The earliest color holograms were transmission holograms, and the images were reconstructed using the original laser wavelengths following the same path as the original reference beam. In essence, three different holograms were recorded and reconstructed so that colors were created by additive color mixing.

A major problem in color holography is that the three sets of fringes formed by the three beams occupy the same volume in the emulsion, and this leads to cross-talk. That is, in addition to the light of the wavelength used to record it, each hologram diffracts the other two wavelengths as well. The set of fringes formed by the red laser reconstructs not only the true red image but also spurious images from the fringes formed by the green and blue laser beams. The same thing happens for the green and blue beams, leading to six sets of spurious images in addition to the three genuine images.

One way to deal with the cross-talk difficulty, in part, is by using a thick emulsion and a large angle of incidence for the reference beam. When such a hologram is illuminated with the original multiwavelength reference beam, each wavelength is diffracted with maximum efficiency by its original set of fringe planes, producing a multicolored image, but the cross-talk images are attenuated since they do not satisfy the Bragg condition.

The highest wavelength selectivity is obtained with thick-emulsion ("volume") reflection holograms; such holograms can even reconstruct a monochromatic image when illuminated with white light. Thus, they work well with color holography.

To produce a multicolor image, a volume reflection hologram is recorded with three wavelengths so that one set of fringe planes is produced for each wavelength. When such a hologram is illuminated with white light, each set of fringe planes diffracts light of the color (wavelength) used to record it.

Two other difficulties occur in color holography: color distortion due to shrinkage of the emulsion during processing and scattering of blue light in the emulsion. These difficulties appear to be minimized by the use of photopolymeric materials in place of photographic emulsions.

The process of making color holograms has recently been greatly simplified. The Litiholo company has developed a process using red, green, and blue laser diodes and a self-developing film that obviates the need for developing chemicals. The color hologram shown in Fig. 11.12, which can be viewed in white light, was produced in just minutes.

Lippmann Color Holograms

About the turn of the century, Gabriel Lippmann developed an experimental technique for making color photographs that made use of Bragg reflection and showed striking similarity to holography. A photograph using this method is shown in Fig. 11.13. In 1908, Lippmann won the Nobel Prize for his invention, but it never became very practical partly because of the unavailability of fine-grain photographic emulsions in his day. His idea of recording interference fringes throughout the depth of the emulsion was used by Denisyuk when he introduced the technique of recording single-beam reflection holograms in the early 1960s. Some holographers refer to single-beam reflection holograms as *Lippmann holograms*, while others reserve that term for color reflection holograms only.

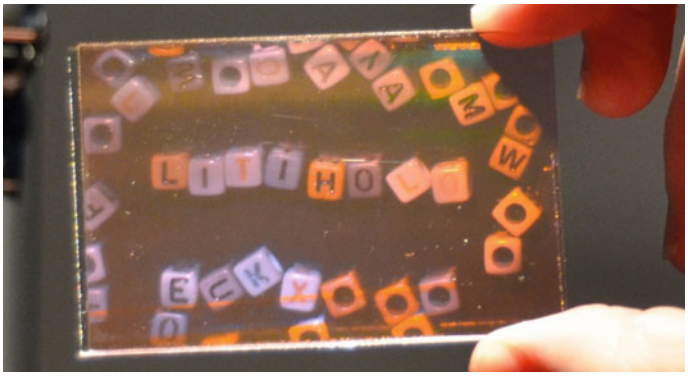


Fig. 11.12 A color hologram produced using red, green, and blue laser diodes and self-developing film (Courtesy of Litiholo)

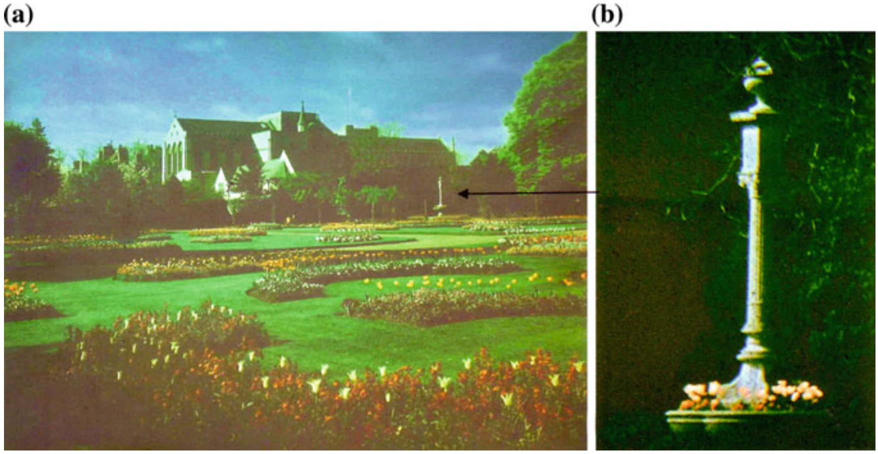


Fig. 11.13 **a** Lippmann photograph of Abby Gardens, Bury St. Edmunds. **b** Detail from photograph (Lippmann photograph courtesy of Hans Bjelkhagen)

For a Lippmann hologram, the recorded interference fringes are quite narrow, and hence a recording material with extremely high resolution is necessary to obtain a satisfactory image. Although silver halide emulsions are satisfactory for recording holograms with red light, some holographers have found it better to use a dichromated gelatin plate for the blue and green components. The two plates are then combined to produce the final hologram.

Multicolor Rainbow Holograms

To produce a multicolor rainbow hologram, three primary holograms are made using red, green, and blue laser light. The transfer of the images (see Sect. 11.4) from these three primary holograms to a single hologram can be done sequentially through a narrow slit using red, blue, and green laser light, or it can be done with a single laser. When this multiplexed hologram is illuminated with white light, three reconstructed images are superimposed, as well as three images of the viewing slit. However, these slit images or spectra are displaced vertically with respect to each other, so that each component of the hologram reconstructs an image in its original position in the color with which it was made, and the observer sees three superimposed images in the colors with which the primary holograms were made.

Pseudocolor Through Shrinkage

Another way to produce color, or more properly "pseudocolor," in a reflection hologram is to "tune" the thickness of the recording medium by selective shrinkage. Suppose that the red component hologram is recorded first, using a red He–Ne laser, with the emulsion side of the plate toward the reference beam. This plate is bleached and treated to eliminate emulsion shrinkage. Then the green component is recorded on another plate, again using the red beam from the He–Ne laser, but with the emulsion side toward the object beam. The emulsion is soaked in a solution of triethanolamine, a chemical swelling agent, and dried in darkness; the blue component is then recorded on the swollen emulsion. Normal bleach processing eliminates the triethanolamine and produces the usual shrinkage. The first exposure yields a green image and the second one a blue image. After drying, the red and the green/blue plates are cemented together with their emulsions in contact.

Very good pseudocolor images can also be produced from contact copies of three master holograms made on photopolymer film. Two of the copies are swollen during processing so that they reconstruct green and red images. DuPont makes a single-layer three-color photopolymer.

11.7 Multiple Scenes

One of the most dramatic features of a hologram is that it is capable of recording more than one independent scene, either by multiple exposure or by making transfer holograms from several masters. These images can be viewed independently by changing the angle between the plane of the hologram and the reference beam.

To record multiple scenes, one exposes the film with the first object, stops the exposure, changes to a second object, changes the angle between the reference beam and the film, and exposes the film a second time. To create multiple images by transfer from master holograms, the masters are generally masked down to narrow slits either horizontally or vertically, and they are all transferred at once.

Recording multiple scenes is, in general, practical only in transmission holograms. The smaller and farther the objects are from the hologram, the more channels you can record. It is usually not possible to record multiple scenes using reflection holography.

11.8 Holographic Stereograms

An ordinary photographic image is two-dimensional. Recreating a three-dimensional scene requires two photographs taken from slightly different angles (a "stereo" pair), each viewed with one eye. In the old-fashioned stereopticon, the two images were viewed through two lenses separated by a wooden barrier. In modern 3D movies, the two images are viewed through polarized glasses so that each eye sees only one of them. In parallax stereograms, once popular as postcards, two photographic images are printed in narrow vertical strips and mounted under a fine lenticular screen that allows only one image to be seen by each eye.

A holographic stereogram, also often referred to alternately as an integral hologram or multiplex hologram, reconstructs a three-dimensional image from a series of two-dimensional views of an object recorded from different angles. A camera is used to record a subject from equally spaced positions along a horizontal line. A hologram is then made from each frame. An obvious advantage of

Fig. 11.14 *The Kiss II* by Lloyd Cross. As you walk by the hologram, a woman is seen blowing you a kiss. She then winks at you (Courtesy of The Jonathan Ross Hologram Collection)

this technique is that a laser is not required for the initial photographs, which is especially advantageous for recording large scenes or human subjects. Another advantage of the process is that the final product can be viewed using white light.

The first holographic stereogram was produced in 1974 by Lloyd Cross. He combined traditional filmmaking with holography to produce moving three-dimensional images, one of his best known being *The Kiss II*, shown in Fig. 11.14. Illuminated by a white light bulb, the hologram is mounted in a semicircular display. As an observer walks by, a three-dimensional image of a woman, seemingly floating behind the surface of the hologram, is seen blowing a kiss and winking.

Full-color stereograms are particularly impressive. The first stage in creating such a stereogram is to make a set of color-separation positives in black and white from the original color transparencies or negatives. From these, three masters are made, one for the red-separation original, one for the green, and one for the blue. The transfer hologram is exposed to the real image of each hologram, in turn, each film being positioned appropriately along the transfer slit.

11.9 Embossed Holograms

Although holograms can be copied photographically, mass production by this method is not economical. The wide use of holograms in advertising, in books, on credit cards, and even on money requires an inexpensive way of reproduction such as embossing copies in plastic. Although it appears reflective, an embossed hologram should really be thought of as a *transmission hologram* with a mirror behind it.

Master holograms for embossing are made on photoresist material, which records the primary holographic fringes in relief. The photoresist master may be recorded directly on the photoresist, or it may be copied from the original hologram by using a high-power laser. The surface of the photoresist is sprayed or vacuum-coated with a conductive coating, which is then electroplated to the desired thickness. The electroformed coating is separated from the photoresist to be used as the metal master. Second-generation masters can be made from the original master by electroforming.

Giveaway holograms for advertising and adorning cereal boxes are usually hot pressed on polyvinyl chloride (PVC) or polyester. After pressing, the embossed side is aluminized to convert the transmission hologram into a reflection hologram. Holograms for credit cards, banknotes, and magazines are usually produced by hot stamping to give a flush surface so that the hologram cannot be removed without destroying it.

11.10 Holographic Interferometry

In addition to the primary fringes that appear in all holograms due to interference between the object and reference beams, much larger secondary fringes may appear if the object has moved during the exposure. These secondary fringes have been used to study stress, motion, and vibration, for example. Since its discovery by Powell and Stetson in 1965, holographic interferometry has become one of the most important research and industrial applications of holography.

Real-Time Interferometry

If the photographic plate is processed in the plate holder or replaced in the exact position it was during exposure, the object will coincide with its own image. If the object has moved ever so slightly, however, interference fringes appear, and these fringes can be used to determine precisely how much the object has moved or changed. Unlike other interferometric techniques, which require optically polished surfaces, holographic interferometry works with rough surfaces as well.

Real-time interferometry can be used to view the normal modes of a vibrating body. The hologram is carefully adjusted to minimize the real-time fringes with the object at rest, and then the object is made to vibrate at each of the modal frequencies of interest. Fringe patterns produce a sort of contour map of the displacement in each normal mode.

Time-Averaged Interferometry

A vibrating object is instantaneously stationary at the two extremes of its motion while it moves at maximum speed somewhere near the center. On the average, therefore, it spends more time near the turning points, and so a hologram of it with a long exposure will show a pattern of interference fringes that indicates its displacement difference at the two turning points. Time-averaged interferograms of a handbell and guitar are shown in Fig. 11.15. The photographs show a reconstruction of normal modes of vibration. Nodes appear as bright lines, and antinodes as bull's eyes. Each bright fringe surrounding the antinodes represents an amplitude change of one-quarter of the wavelength of light, so an accurate contour map of the vibrational motion is obtained.

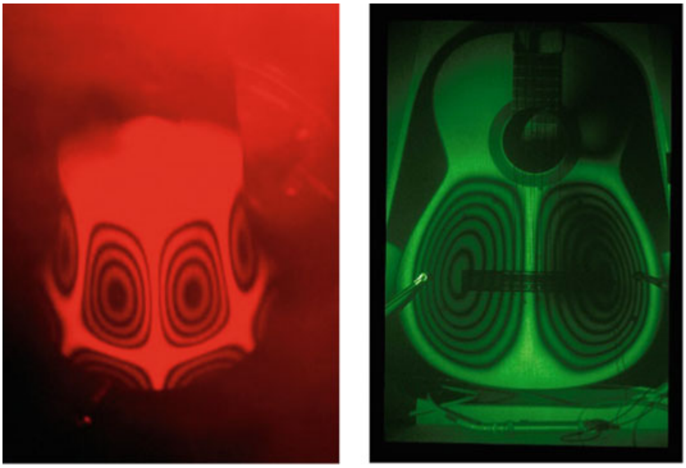


Fig. 11.15 Time-averaged hologram interferograms of a handbell (Photograph courtesy of Professor Thomas Rossing, Stanford University) and guitar (Photograph courtesy of Dr. Bernard Richardson, Cardiff University)

11.11 TV Holography

Although holograms recorded on film generally have the highest possible resolution, the use of film is somewhat time-consuming. It is much more convenient to create the holographic images electronically so that they can be viewed as soon as they are created. In the 1970s, video techniques to record holograms or speckle patterns, as they are sometimes called, developed. TV holography, or electronic speckle pattern interferometry (ESPI), allows real-time fringes to be presented on a TV monitor without any photographic processing.

A modern TV holography system, such as the one shown in Fig. 11.16, uses a sensitive CCD (charge-coupled device) camera, and incorporates image processing using digital computers and techniques such as phase stepping. TV holography has become popular in engineering laboratories and in industry to study vibrations, deformations, and sound fields, and is used in nondestructive testing. One of its first applications in the arts has been the study of vibrations in musical instruments. It has not yet been widely used by visual artists to create real-time holographic images, however.

An optical system for TV holography is shown in Fig. 11.17. A beam splitter (BS) divides the laser light to produce a reference and an object beam. The reference beam illuminates the CCD camera via a phase-stepping mirror (PS) and an optical fiber (see Fig. 4.15), while the object beam illuminates the object to be studied. Reflected light from the object reaches the CCD camera where it interferes with the reference beam to produce the holographic image. The speckle-averaging mechanism (SAM) in the object beam alters the illumination angle in small steps in

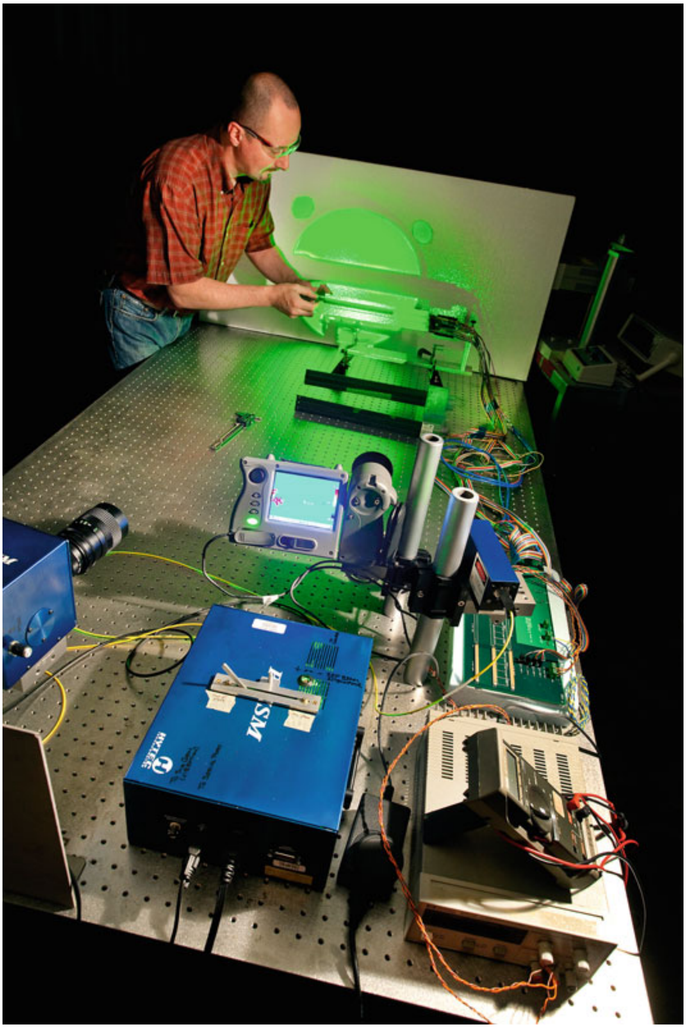


Fig. 11.16 TV holography distortion measurement system at Lawrence Berkeley National Laboratory (U.S. Department of Energy from United States [Public domain], via Wikimedia Commons)

order to reduce laser speckle noise in the interferograms. The system in Fig. 11.17 is designed to detect small deformations or vibrations of the object in the direction of the laser beam. Other systems are designed to detect deformations parallel to the surface of the object.

An interferogram of a vibrating square plate is shown in Fig. 11.18. The plate is driven by a force that oscillates at the frequency of one of the plate's vibrational modes.

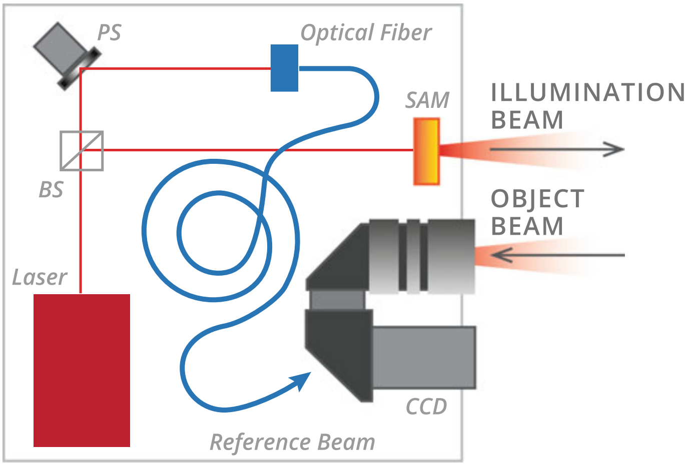
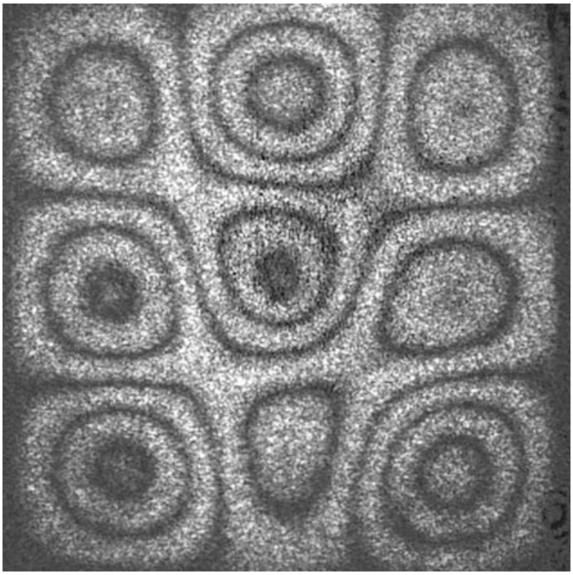


Fig. 11.17 Optical system for TV holography. BS = beam splitter; PS = phase-stepping mirror; SAM = speckle-averaging mechanism; CCD = video camera

Fig. 11.18 Electronic speckle pattern interferometry (ESPI) fringes showing a vibration mode of a clamped square plate (Epzcaw [Public domain], from Wikimedia Commons)



11.12 Photopolymers

A *photopolymer* is a material that changes its chemical composition upon exposure to light: in particular, simpler molecules called *monomers* are coaxed to form complex polymers. Photopolymers can record photographic or holographic images, and they require no development. In recording, the material is first exposed to the information-carrying light. Then the material is exposed to regular light of uniform intensity until the remaining monomers also polymerize.

Photopolymers generally require longer exposure times than photographic films and they have relatively short shelf life. They can be made to respond to light of almost any color. DuPont has developed a photopolymer called OmniDex that is intended for holography.

11.13 Computer-Generated Holograms

Theoretically, computers can be used to produce holograms with any desired amplitude and phase distribution. In practice, this is easier said than done. Nevertheless, a lot of research has been directed to advancing this very promising field of imaging.

The first step in generating a hologram by computer is to calculate the complex amplitude of the object wave at the hologram plane, which is generally taken to be a mathematical (Fourier) transform of the complex amplitude in the object plane. This was done in the production of the hologram shown in Fig. 11.19. If the object wave is sampled at a sufficiently large number of points, this can be done with no loss of information. The second step is to produce a transparent hologram that will reconstruct the object wave when suitably illuminated. To do this, the computer is used to control a plotter that produces a large-scale version of the hologram that is photographically reduced to produce the required transparency.

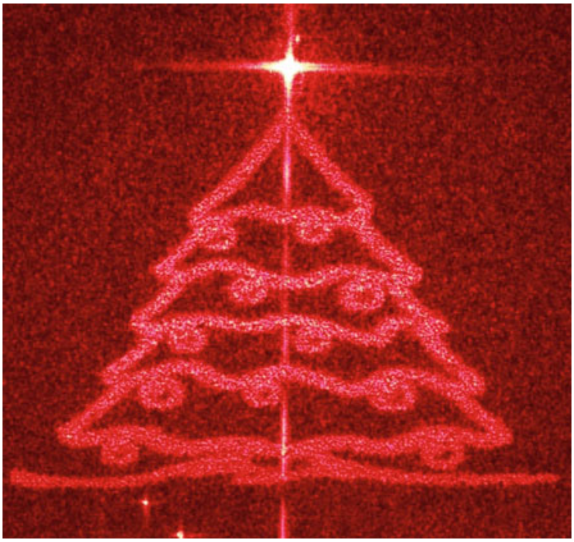


Fig. 11.19 A computer-generated hologram (Alexander Macfaden (https://commons.wikimedia.org/wiki/File:CGH_XmasTree.jpg), "CGH XmasTree", https://creativecommons.org/licenses/by-sa/3.0/legalcode)

11.14 Holography in the Arts

Can holography be considered an art form? This question has been asked ever since the revolutionary method of recording three-dimensional images became widely available in the late 1960s. Initially viewed by the art community as a scientific curiosity, holography later became seen by many visual artists as a medium with unlimited potential. Today, holographic images can be found in art galleries around the world, demonstrating the continuing marriage of art and science.

Salvador Dali is credited as one of the first artists to enthusiastically embrace holography as an artistic medium. Dali's interest in optics, and its application in his art, preceded the arrival of holography. Throughout his career he had experimented with moiré patterns and stereoscopic imagery, so it is perhaps not surprising that the artist became fascinated with the new three-dimensional canvas. Dali's enthusiasm for holography is evident from the following quote: "With the genius of Gabor, the possibility of a new Renaissance in art has been realized with the use of holography. The doors have been opened for me into a new house of creation."

From 1971 to 1976, Dali produced seven holographic works that were to become some of the most important art holograms of the twentieth century. It is this body of work that most certainly inspired others to use laser light as a brush.

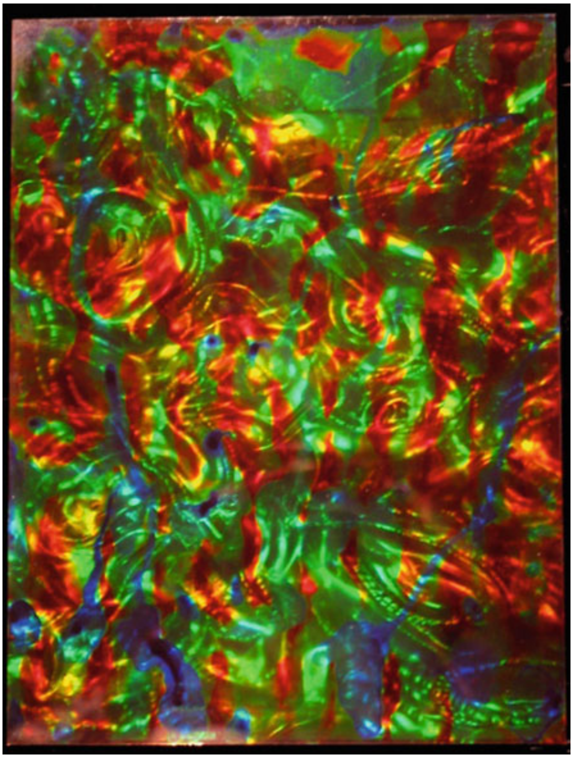


Fig. 11.20 *Aleph 2* by Eric Leiser (Eric Leiser (https://commons.wikimedia.org/wiki/File:Aleph2.jpg), "Aleph2", https://creativecommons.org/licenses/by-sa/3.0/legalcode)

In the decades following Dali's monumental contributions to the creative use of holography, scores of visual artists have become devotees of the art form. Among them is filmmaker and holographer Eric Leiser. One of his holographic creations, *Aleph 2*, is shown in Fig. 11.20.

11.15 Summary

Optical holography is a technique for the recording and reconstruction of three-dimensional images using photographic film or digital storage. Unlike a conventional photograph, there is no reproduction of the object on film. Instead, the film is used to record an interference pattern. An observer looks through a hologram as if it were a window and sees a three-dimensional image on either side or even straddling this window. A reflection hologram can be viewed with a spotlight or a point light source as if it were a three-dimensional painting. A transmission hologram is illuminated from behind by monochromatic light. In addition to basic transmission and reflection holograms, there are many special types such as volume holograms, rainbow holograms, multiplex holograms, and holographic interferograms.

Recording a hologram requires a reference beam and an object beam, while reconstructing the image requires a reference beam only. Mass production of holograms is made possible by embossing them in plastic from a master. Color holograms require three beams of monochromatic coherent light to record three different holographic images. The three reconstructed images are viewed together, so they combine additively to give a color image.

Holographic interferometry is widely used to measure distortion or vibration of an object. Time-averaged interferometry records the modes of vibration with a very high resolution. TV holography allows the viewing of electronically produced interferograms in real time.

Holography is seen by many visual artists as a medium with limitless possibilities. Now accepted as an exciting new art form, holograms can now be found in galleries and private collections.

◆ Review Questions

1. How is it possible for a two-dimensional hologram to produce a three-dimensional image?
2. Why is a laser required in the production of a hologram?
3. If a hologram is broken into two pieces and the two pieces are viewed at the same time, what will be seen?
4. Could two different lasers be used to produce the object beam and reference beam? Why?
5. Why can a reflection hologram be viewed in sunlight but a transmission hologram cannot?

6. Explain why vibration must be avoided when making a hologram.
7. What is a holographic stereogram?
8. What type of hologram is produced by shining light through the film to illuminate the object? How can this approach be used to produce a full color image?
9. Is an embossed hologram a transmission or reflection hologram? Explain your answer.
10. How is a holographic stereogram produced?

▼ Questions for Thought and Discussion

1. How is it possible to produce a holographic image that projects in front of the hologram?
2. How are multiple scenes recorded on a single hologram?
3. Is it possible to determine what is recorded on a hologram without actually reconstructing the image? Explain.
4. Discuss problems associated with making a hologram of a person. Suggest how these difficulties might have been overcome in the creation of the hologram of Dennis Gabor (Fig. 11.1).

● Experiments for Home, Laboratory, and Classroom Demonstration

Home and Classroom Demonstration

1. **Reflection hologram**. Examine a simple reflection hologram in different types of light (including sunlight).
2. **Make a reflection hologram**. Create a reflection hologram using a Holokit™ hologram kit available from Integraf (https://www.integraf.com/) or a Litiholo hologram kit (https://litiholo.com/). The Litiholo kit simplifies the holographic process by employing a self-developing film, thus eliminating the need for chemicals. See Experiments 11.1 and 11.2 for detailed instructions on making both reflection and transmission holograms.
3. **Holography Museum**. Visit a holography museum. How many different kinds of holograms can you identify?
4. **Bright stripe in front of a rainbow hologram**. Hold a rainbow hologram very flat and illuminate it from above with a monochromatic source at least 2 m away. With your head about 1 m in front of the hologram, look for a glowing horizontal stripe floating about half a meter in front of the hologram. (The stripe can be located by bobbing your head up and down and positioning a finger in space until there is no relative motion between it and the stripe.) If you bring your eyes into this glowing stripe, you will suddenly see the entire 3D image. You can "look around" as you move from side to side, but do not "look under or over," because the image disappears.

Now illuminate the hologram with a point-like source of white light and view the hologram through an interference filter to see the glowing stripe in front of it in whatever color the filter transmits. Tilt the interference filter so that its transmission color shifts toward the blue, and note that the stripe location moves downward. Without the filter, you should see a spectrum hanging in front of the hologram with red on top and blue on the bottom. (This experiment was suggested by Stephen Benton, inventor of the rainbow hologram; see *Optics and Photonics News*, July 1991.)

4. Project real and virtual images from a transmission hologram and determine whether the images are orthoscopic or pseudoscopic. Determine the depth of field for each image.

Laboratory (See Appendix J)

11.1 Making a Reflection Hologram
11.2 Making a Transmission Hologram

Glossary of Terms

amplitude hologram A hologram that modulates the reference beam through absorption.

bleaching Dissolving silver particles to make the emulsion more transparent and the reconstructed image brighter. Bleaching changes an amplitude hologram into a phase hologram.

Bragg reflection Strong reflection at certain angles by diffraction of light from planes of recorded fringes. Bragg's law shows how the angle depends upon the spacing of the planes and the wavelength of the light.

coherent light Light having a fixed relationship between the phase of light waves of a single wavelength.

Denisyuk hologram A reflection hologram in which a single beam serves as both reference beam and object beam by passing through the emulsion twice.

hologram A recording of interference fringes from which a three-dimensional image can be reconstructed.

holographic interferogram A holographic recording using two or more images to show motion or some other time-dependent phenomenon.

Lippmann photography A technique for making color photographs that makes use of Bragg reflection.

object beam Portion of the laser beam that illuminates the object.

orthoscopic image A holographic image that has normal front to back perspective.

phase hologram A transparent hologram in which the fringes modulate the phase of the reference beam during image reconstruction.

pseudocolor hologram A hologram in which the emulsion thickness is varied to produce colors different from the light used to record it.

pseudoscopic image An image that is reversed front to back.

rainbow hologram A hologram whose image changes color as the viewpoint is moved up and down.

real image An image that can be projected on a screen.

real-time holographic interferometry Creating an interference pattern between an object and its hologram in order to see how much the object has moved or changed.

reference beam Portion of the laser beam that goes directly to the film or camera.

reflection hologram A hologram that can be viewed from the front as if it were a painting.

time-average interferogram Combining many holograms in the same image; in the case of a vibrating object, the nodes appear as bright lines and fringes of equal amplitude occur in the antinodal regions.

transfer hologram Hologram that uses the real image from another hologram as its object.

transmission hologram A hologram that is viewed by illuminating it from behind with monochromatic light.

TV hologram A hologram that is created by electronically comparing the reference beam and the object beam.

virtual image An image that cannot be projected on a screen.

Further Reading

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