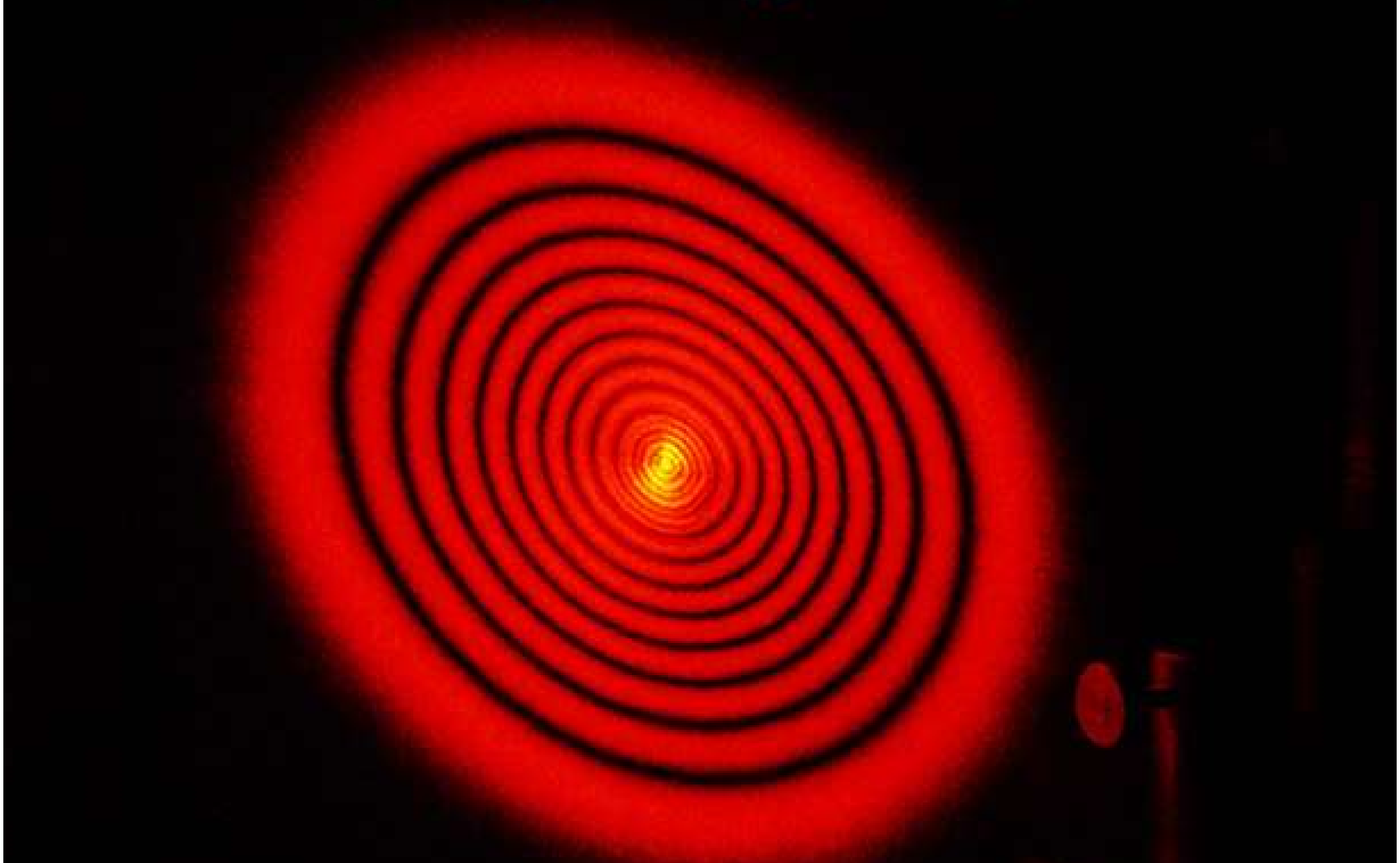
An Introduction to

Holography

(Concepts and Applications)



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First Edition, 2012

ISBN 978-81-323-2308-2

Published by:
Library Press
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

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Chapter- 1

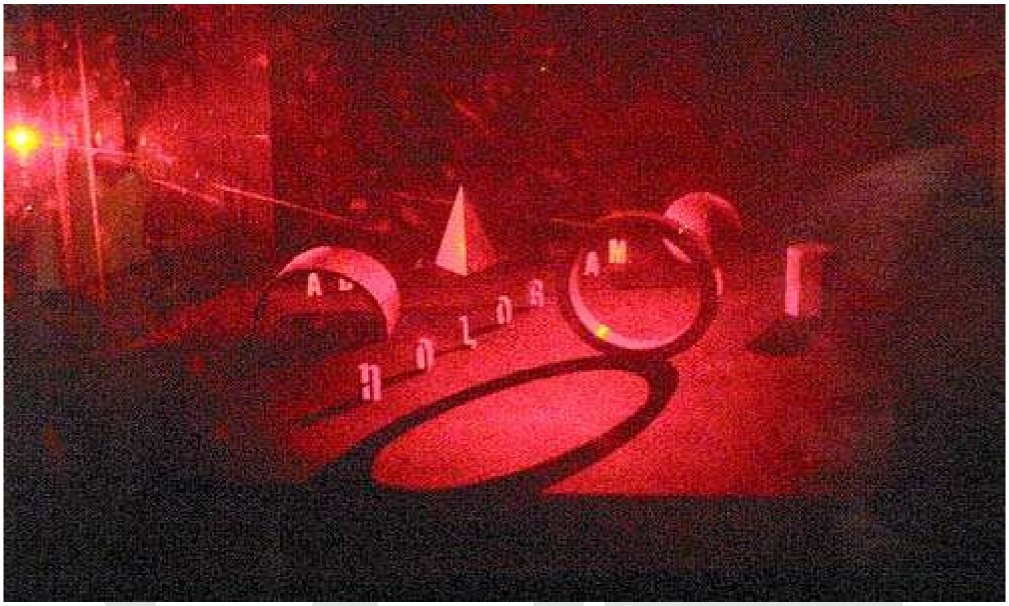
Holography

Identigram as a security element in a German identity card

Holography (from the Greek, ὅλος *hólos* whole + γραφή *grafē* writing, drawing) is a technique that allows the light scattered from an object to be recorded and later reconstructed so that it appears as if the object is in the same position relative to the recording medium as it was when recorded. The image changes as the position and orientation of the viewing system changes in exactly the same way as if the object were still present, thus making the recorded image (**hologram**) appear three dimensional.

The technique of holography can also be used to optically store, retrieve, and process information. While it has been possible to create a 3-D holographic picture of a static object since the 1960s, it is only in the last few years that arbitrary scenes or videos can be shown on a holographic volumetric display.

Overview and history



Hologram Artwork in MIT Museum

Holography was invented in 1947 by the Hungarian-British physicist Dennis Gabor (Hungarian name: Gábor Dénes), work for which he received the Nobel Prize in Physics in 1971. Pioneering work in the field of physics by other scientists including Mieczysław Wolfke resolved technical issues which previously had prevented advancement. The discovery was an unexpected result of research into improving electron microscopes at the British Thomson-Houston Company in Rugby, England, and the company filed a patent in December 1947 (patent GB685286). The technique as originally invented is still used in electron microscopy, where it is known as electron holography, but holography as a light-optical technique did not really advance until the development of the laser in 1960.

The first practical optical holograms that recorded 3D objects were made in 1962 by Yuri Denisyuk in the Soviet Union and by Emmett Leith and Juris Upatnieks at University of Michigan, USA. Advances in photochemical processing techniques to produce high-quality display holograms were achieved by Nicholas J. Phillips.

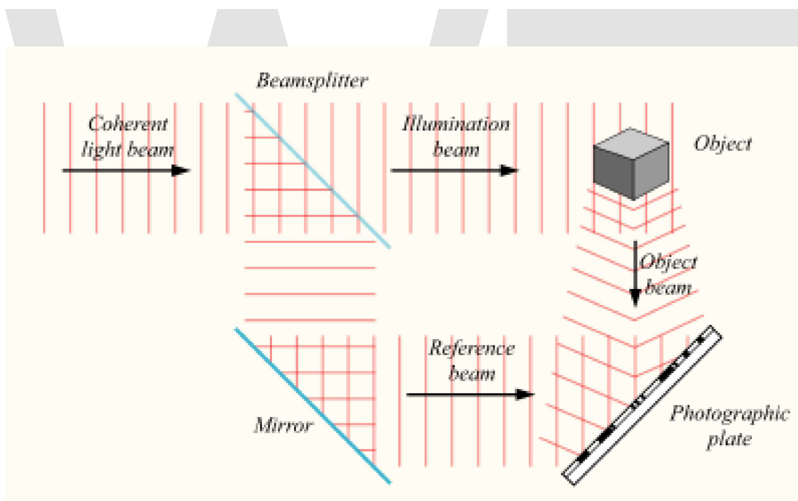
Several types of holograms can be made. Transmission holograms, such as those produced by Leith and Upatnieks, are viewed by shining laser light through them and looking at the reconstructed image from the side of the hologram opposite the source. A later refinement, the "rainbow transmission" hologram, allows more convenient illumination by white light rather than by lasers. Rainbow holograms are commonly seen today on credit cards as a security feature and on product packaging. These versions of the rainbow transmission hologram are commonly formed as surface relief patterns in a plastic film, and they incorporate a reflective aluminum coating that provides the light from "behind" to reconstruct their imagery.

Another kind of common hologram, the reflection or Denisyuk hologram, is capable of multicolour image reproduction using a white light illumination source on the same side of the hologram as the viewer.

Specular holography is a related technique for making three dimensional imagery by controlling the motion of specularities on a two-dimensional surface. It works by reflectively or refractively manipulating bundles of light rays, whereas Gabor-style holography works by diffractively reconstructing wavefronts.

One of the most promising recent advances in the short history of holography has been the mass production of low-cost solid-state lasers, such as those found in millions of DVD recorders and used in other common applications, which are sometimes also useful for holography. These cheap, compact, solid-state lasers can, under some circumstances, compete well with the large, expensive gas lasers previously required to make holograms, and are already helping to make holography much more accessible to low-budget researchers, artists and dedicated hobbyists.

Theory



Holographic recording process

Though holography is often referred to as 3D photography, this is a misconception. A better analogy is sound recording where the sound field is encoded in such a way that it can later be reproduced. In holography, some of the light scattered from an object or a set of objects falls on the recording medium. A second light beam, known as the reference beam, also illuminates the recording medium, so that interference occurs between the two beams. The resulting light field generates a seemingly random pattern of varying intensity which is recorded in the hologram. It can be shown that if the hologram is illuminated by the original reference beam, the reference beam is diffracted by the hologram to produce a diffracted light field which is identical to the light field which was scattered by the object or objects. Thus, someone looking into the hologram "sees" the objects even though they are no longer present. There are a variety of recording materials which can be used, including photographic film.

The first cameras used something called a "pinhole lens". They consisted of a completely blacked-out box with a tiny pinhole on the side away from the film or screen. As a result, they only caught the scene before them from a single, tiny vantage point. The glass lenses that followed, were, in effect, simply giant pinholes, with all the light they collected being passed through a tiny point—a pinhole as it were—at the focal point of the glass lens before spreading out again before hitting the film or screen behind the lens.

The problem Dennis Gabor, the inventor of holography, set out to solve was how to take a picture of all the light passing through a large window, rather than just the light passing through one tiny pinhole. The person looking through this captured "window" would see the image in 3D by virtue of each of his or her eyes seeing the scene from a different viewpoint. Further, the person would be able to move his or her head around to the extent the window would allow to see the object from a variety of vantage points. (An early hologram from the 1960s featured an object with a glass magnifying lens mounted a few inches/centimeters in front of it. The viewer could, by ducking and bobbing his or her head, "look through" the image of the magnifier and, just as with a real magnifier, see different parts of the object behind it enlarged as they swept into view.)

Dennis Gabor, in effect, needed a fast shutter, one so fast that it could "freeze" all the light waves at their current phase just as they were passing through the window, a shutter that moved at the speed of light. His successful approach worked in a way analogous to the way a strobe light is used to "freeze" the motion of rapidly moving mechanical equipment, such as engines: If the light comes on at exactly the same moment during every rotation of a piece of equipment, the rotating part(s) will appear to be standing still.

The function analogous to a strobe light, in holography, is performed by the "reference beam." As you can see in the illustration above, a portion of the light from the laser, the "illumination beam," is aimed at the scene where it bounces off the objects in the scene directly onto the film—the window—with no pinhole or lens interposed. Another portion of the laser light, the "reference beam," instead of striking the object first, is split off from the original laser beam and directed straight onto the film.

To "play back" the scene, one resupplies the reference beam, shining it onto the developed film—the window. This reveals the originally-captured phase of the light waves as they passed through the window on their way from the objects in the scene. In effect, as the illustration shows, you can now "look through" the window and see the original object behind it.

Dennis Gabor's invention was not nearly as simple as a strobe light. To go deeper into the theory of holography, it is next necessary to understand Interference and diffraction.

Interference and diffraction

Interference occurs when one or more wavefronts are superimposed. Diffraction occurs whenever a wavefront encounters an object. The process of producing a holographic reconstruction is explained below purely in terms of interference and diffraction. It is somewhat simplified, but is accurate enough to provide an understanding of how the holographic process works.

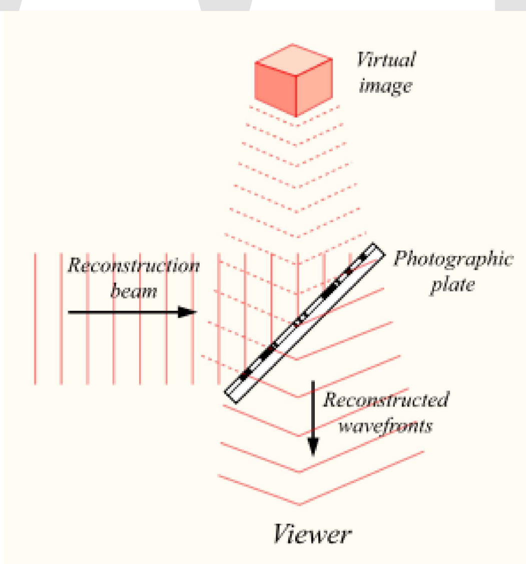
Plane wavefronts

A diffraction grating is a structure with a repeating pattern. A simple example is a metal plate with slits cut at regular intervals. Light rays travelling through it are bent at an angle determined by λ, the wavelength, and d, the distance between the slits, and is given by $\sin\theta = \lambda/d$.

A very simple hologram can be made by superimposing two plane waves from the same light source. One (the reference beam) hits the photographic plate normally and the other one (the object beam) hits the plate at an angle θ. The relative phase between the two beams varies across the photographic plate as $2\pi\ y \sin\theta/\lambda$ where y is the distance along the photographic plate. The two beams interfere with one another to form an interference pattern. The relative phase changes by 2π at intervals of $d = \lambda/\sin\theta$ so the spacing of the interference fringes is given by d. Thus, the relative phase of object and reference beam is encoded as the maxima and minima of the fringe pattern.

When the photographic plate is developed, the fringe pattern acts as a diffraction grating and when the reference beam is incident upon the photographic plate, it is partly diffracted into the same angle θ at which the original object beam was incident. Thus, the object beam has been reconstructed. The diffraction grating created by the two waves interfering has *reconstructed* the "object beam" and it is therefore a hologram as defined above.

Point sources



Holographic reconstruction process

A slightly more complicated hologram can be made using a point source of light as object beam and a plane wave as reference beam to illuminate the photographic plate. An interference pattern is formed which in this case is in the form of curves of decreasing separation with increasing distance from the centre (basically a sinusoidal zone plate).

The photographic plate is developed giving a complicated pattern which can be considered to be made up of a diffraction pattern of varying spacing. When the plate is illuminated by the reference beam alone, it is diffracted by the grating into different angles which depend on the local spacing of the pattern on the plate. It can be shown that the net effect of this is to reconstruct the object beam, so that it appears that light is coming from a point source behind the plate, even when the source has been removed. The light emerging from the photographic plate is identical to the light that emerged from the point source that used to be there. An observer looking into the plate from the other side will "see" a point source of light whether the original source of light is there or not.

This sort of hologram is effectively a concave lens, since it "converts" a plane wavefront into a divergent wavefront. It will also increase the divergence of any wave which is incident on it in exactly the same way as a normal lens does. Its focal length is the distance between the point source and the plate.

Complex objects

To record a hologram of a complex object, a laser beam is first split into two separate beams of light using a beam splitter of half-silvered glass or a birefringent material. One beam illuminates the object, reflecting its image onto the recording medium as it scatters the beam. The second (reference) beam illuminates the recording medium directly.

According to diffraction theory, each point in the object acts as a point source of light. Each of these point sources interferes with the reference beam, giving rise to an interference pattern. The resulting pattern is the sum of all *point source* + *reference beam* interference patterns.

When the object is no longer present, the holographic plate is illuminated by the reference beam. Each point source diffraction grating will diffract part of the reference beam to reconstruct the wavefront from its point source. These individual wavefronts add together to reconstruct the whole of the object beam.

The viewer perceives a wavefront that is identical to the scattered wavefront of the object illuminated by the reference beam, so that it appears to him or her that the object is still in place. This image is known as a "virtual" image as it is generated even though the object is no longer there. The direction of the light source seen illuminating the virtual image is that of the original illuminating beam.

Mathematical model

A light wave can be modeled by a complex number **U** which represents the electric or magnetic field of the light wave. The amplitude and phase of the light are represented by the absolute value and angle of the complex number. The object and reference waves at any point in the holographic system are given by $\mathbf{U}_O$ and $\mathbf{U}_R$. The combined beam is given by $\mathbf{U}_O + \mathbf{U}_R$. The energy of the combined beams is proportional to the square of magnitude of the electric wave:

$$|U_O + U_R|^2 = U_O U_R^* + |U_R|^2 + |U_O|^2 + U_O^* U_R$$

If a photographic plate is exposed to the two beams, and then developed, its transmittance, **T**, is proportional to the light energy which was incident on the plate, and is given by

$$T = k[U_O U_R^* + |U_R|^2 + |U_O|^2 + U_O^* U_R]$$

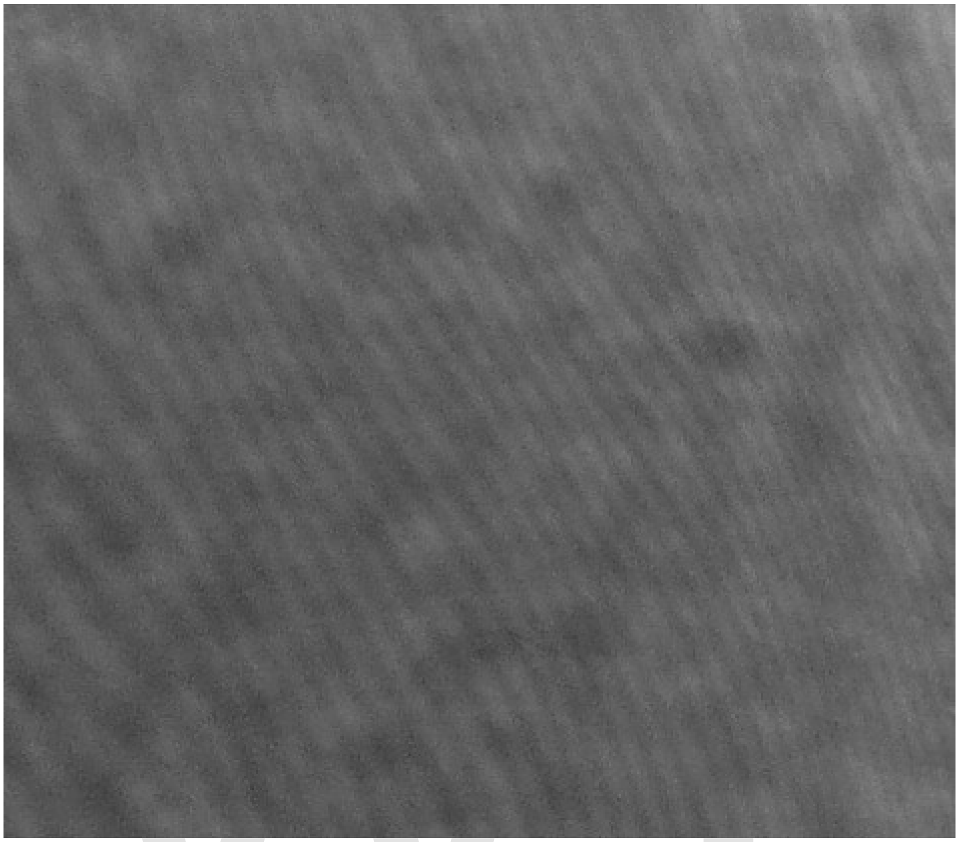
where k is a constant. When the developed plate is illuminated by the reference beam, the light transmitted through the plate, $\mathbf{U}_H$ is

$$U_H = TU_R = k[U_O U_R^* + |U_R|^2 + |U_O|^2 + U_O^* U_R]U_R = k[U_O|U_R|^2 + |U_R|^2 U_R + |U_O|^2 U_R + U_O^* U_R^2]$$

It can be seen that $\mathbf{U}_H$ has four terms. The first of these is proportional to $\mathbf{U}_O$, and this is the re-constructed object beam. The second term represents the reference beam whose amplitude has been modified by $\mathbf{U}_R^2$. The third also represents the reference beam which has had its amplitude modified by $\mathbf{U}_O^2$; this modification will cause the reference beam to be diffracted around its central direction. The fourth term is known as the "conjugate object beam." It has the reverse curvature to the object beam itself, and forms a real image of the object in the space beyond the holographic plate.

Early holograms had both the object and reference beams illuminating the recording medium normally, which meant that all the four beams emerging from the hologram were superimposed on one another. The off-axis hologram was developed by Leith and Upatnieks to overcome this problem. The object and reference beams are incident at well-separated angles onto the holographic recording medium and the virtual, real and reference wavefronts all emerge at different angles, enabling the re-constructed object beam to be imaged clearly.

Viewing the hologram



Photograph of a hologram in front of a diffuse light background - 8x8 mm

The picture on the right is a photograph, taken against a diffuse light background, of a hologram recorded on photographic emulsion. The area shown is about 8 mm by 8 mm. The holographic recording is the random variation in intensity which is an objective speckle pattern, and not the regular lines which are likely to be due to interference arising from multiple reflections in the glass plate on which the photographic emulsion is mounted. It is no more possible to discern the subject of the hologram from this than it is to identify the music on an gramophone record by looking at the structure of the gramophone record surface. When this hologram is illuminated by a divergent laser beam, the viewer will see the object used to make it (in this case, a toy van) because the light is diffracted by the hologram to reconstruct the light which was scattered from the object.

When one looks at a scene, each eye captures a portion of the light scattered from the scene, and the lens of the eye forms an image of the scene on the retina, in which light from each angular position is focused to a specific angular position in the image plane. Since the hologram reconstructs the whole of the scattered light field that was incident on the hologram, the viewer sees the same image whether it is derived from the light field scattered from the object, or the reconstructed light field produced by the hologram, and is unable to tell whether he or she is looking at the real or the virtual object. If the viewer moves about, the object will appear to move in exactly the same way whether he or she is looking at the original light field or the reconstructed light field. If there are several objects in the scene, they will exhibit parallax. If the viewer is using both eyes (stereoscopic vision), he or she will get depth information when viewing the hologram in exactly the same way as when he or she is viewing the real scene.

A hologram is not a 3D photograph. A photograph records an image of the recorded scene from a single viewpoint, which is defined by the position of the camera lens. The hologram is not an image, but an encoding system which enables the scattered light field to be reconstructed. Images can then be formed from any point in the reconstructed beam either with a camera or by eye. It was very common in the early days of holography to use a chess board as the object, and then take photographs at several different angles using the reconstructed light to show how the relative positions of the chess-pieces appeared to change.

Since each point in the hologram contains light from the whole of the original scene, the whole scene can, in principle, be reconstructed from an arbitrarily small part of the hologram. To demonstrate this concept, the hologram can be broken into small pieces and the entire object can still be seen from each small piece. If one envisions the hologram as a "window" on the object, then each small piece of hologram is just a part of the window from which it can still be viewed, even if the rest of the window is blocked off.

One does, however, lose resolution as the size of the hologram is decreased—the image becomes "fuzzier." This is a result of diffraction and arises in the same way as the resolution of an imaging system is ultimately limited by diffraction where the resolution becomes coarser as the lens or lens aperture diameter decreases.

Viewing and authoring

The object and the reference beams must be able to produce an interference pattern that is stable during the time in which the holographic recording is made. To do this, they must have the same frequency and the same relative phase during this time, that is, they must be mutually coherent. Many laser beams satisfy this condition, and lasers have been used to make holograms since their invention, though the first holograms by Gabor used 'quasi-chromatic' light sources. In principle, two separate light sources could be used if the coherence condition could be satisfied, but in practice a single laser is always used.

In addition, the medium used to record the fringe pattern must be able to resolve the fringe patterns and some of the more common media used are listed below. The spacing of the fringes depends on the angle between object and reference beam. For example, if this angle is 45°, and the wavelength of the light is 0.5μm, the fringe spacing is about 0.7μm or 1400 lines/mm. A working hologram can be obtained even if all the fringes are not resolved, but the resolution of the image is reduced as the resolution of the recording medium decreases.

Mechanical stability is also very important when making a hologram. Any relative phase change between the object and reference beams due to vibration or air movement will cause the fringes on the recording medium to move, and if the phase change is greater than π, the fringe pattern is averaged out, and no holographic recording is obtained. Recording time can be several seconds or more, and given that a phase change of π is equivalent to a movement of $\lambda/2$ this is quite a stringent stability requirement.

Generally, the coherence length of the light determines the maximum depth in the scene of interest that can be recorded holographically. A good holography laser will typically have a coherence length of several meters, ample for a deep hologram. Certain pen laser pointers have been used to make small holograms. The size of these holograms is not restricted by the coherence length of the laser pointers (which can exceed several meters), but by their low power of below 5 mW.

The objects that form the scene must, in general, have optically rough surfaces so that they scatter light over a wide range of angles. A specularly reflecting (or shiny) surface reflects the light in only one direction at each point on its surface, so in general, most of the light will not be incident on the recording medium. The light scattered from objects with a rough surface forms an objective speckle pattern that has random amplitude and phase.

The reference beam is not normally a plane wavefront; it is usually a divergent wavefront that is formed by placing a convex lens in the path of the laser beam.

To reconstruct the object exactly from a transmission hologram, the reference beam must have the same wavelength and curvature, and must illuminate the hologram at the same angle as the original reference beam (i.e. only the phase can be changed). Departure from any of these conditions will give a distorted reconstruction. While nearly all holograms are recorded using lasers, a narrow-band lamp or even sunlight is enough to recognize the reconstructed image.

The reconstructed hologram is enlarged if the light used to reconstruct the hologram has a higher wavelength. This initially generated some interest since it seemed to be possible to use X-rays to make holograms of molecules and view them using visible light. However X-ray holograms have not been created to date. This effect can be demonstrated using a light source which emits several different frequencies.

Exact reconstruction is achieved in holographic interferometry where the holographically reconstructed wavefront interferes with the live wavefront, to map out any displacement of the live object, and gives a null fringe if the object has not moved.

Holographic recording media

The recording medium must be able to resolve the interference fringes as discussed above. It must also be sufficiently sensitive to record the fringe pattern in a time period short enough for the system to remain optically stable, i.e. any relative movement of the two beams must be significantly less than λ/2. It is possible to record holograms in certain materials using a high power pulsed laser technique that uses only a couple of nanoseconds to record the holographic pattern.

The recording medium has to convert the interference pattern into an optical element which modifies either the amplitude or the phase of a light beam which is incident upon it. These are known as amplitude and phase holograms respectively. In amplitude holograms the modulation is in the varying absorption of the light by the hologram, as in a developed photographic emulsion which is less or more absorptive depending on the intensity of the light which illuminated it. In phase holograms, the optical distance (i.e., the refractive index or in some cases the thickness) in the material is modulated.

Most materials used for phase holograms reach the theoretical diffraction efficiency for holograms, which is 100% for thick holograms (Bragg diffraction regime) and 33.9% for thin holograms (Raman-Nath diffraction regime, holographic films of typically some μm thickness). Amplitude holograms have a lower efficiency than phase holograms and are therefore used more rarely.

The table below shows the principal materials for holographic recording. Note that these do not include the materials used in the mass replication of an existing hologram. The resolution limit given in the table indicates the maximal number of interference lines per mm of the gratings. The required exposure is for a long exposure. Short exposure times (less than 1/1000 of a second, such as with a pulsed laser) require a higher exposure due to reciprocity failure.

General properties of recording materials for holography. Source:

Material	Reusable	Processing	Type of hologram	Max. efficiency	Required exposure [mJ/cm²]	Resolution limit [mm^{-1}]
Photographic emulsions	No	Wet	Amplitude	6%	0.001–0.1	1,000–10,000
			Phase (bleached)	60%		
Dichromated gelatin	No	Wet	Phase	100%	10	10,000
Photoresists	No	Wet	Phase	33%	10	3,000
Photothermoplastics	Yes	Charge and heat	Phase	33%	0.01	500–1,200
Photopolymers	No	Post exposure	Phase	100%	1–1,000	2,000–5,000
Photochromics	Yes	None	Amplitude	2%	10–100	>5,000
Photorefractives	Yes	None	Phase	100%	0.1–50,000	2,000–10,000
Elastomers	No	None	Phase	--	300	--

Replication of holograms

A hologram sticker on a Nokia mobile phone battery intended to show the battery is genuine (manufactured by Nokia), and not counterfeit.

Holoprinters

A holoprinter is a holographic printing device that can print out full colour digital holograms from a rendered 3D model or a video series. The machine can cost up to half a million dollars and is about the size of a small room. It uses red, green and blue lasers to write a series of dots or holopixels across a holographic medium. The holopixel contains information about the whole image from its own unique perspective. The information for each holopixel is computed from a series of rendered images generated via computer graphics. The holographic medium is typically a polymer film. The film may require development after exposure. It is then laminated on to a hard plastic backing. Printing a digital hologram can take several hours as each holopixel dot has to be written individually in three colours, where the colours overlap within the medium. The size of a holopixel is typically around a square millimeter.

There are only a few digital holoprinter manufacturers in the world, including Geola (Lithuania), View Holographics (UK) and Zebra Imaging (US).

Embossing and mass production

An existing hologram can be replicated, either in an optical way similar to holographic recording, or in the case of surface relief holograms, by embossing. Surface relief holograms are recorded in photoresists or photothermoplastics, and allow cheap mass reproduction. Such embossed holograms are now widely used, for instance as security features on credit cards or quality merchandise. The Royal Canadian Mint even produces holographic gold and silver coinage through a complex stamping process. The first book to feature a hologram on the front cover was *The Skook* (Warner Books, 1984) by JP Miller, featuring an illustration by Miller. That same year, "Telstar" by Ad Infinitum became the first record with a hologram cover and National Geographic published the first magazine with a hologram cover.

The first step in the embossing process is to make a stamper by electrodeposition of nickel on the relief image recorded on the photoresist or photothermoplastic. When the nickel layer is thick enough, it is separated from the master hologram and mounted on a metal backing plate. The material used to make embossed copies consists of a polyester base film, a resin separation layer and a thermoplastic film constituting the holographic layer.

The embossing process can be carried out with a simple heated press. The bottom layer of the duplicating film (the thermoplastic layer) is heated above its softening point and pressed against the stamper so that it takes up its shape. This shape is retained when the film is cooled and removed from the press. In order to permit the viewing of embossed holograms in reflection, an additional reflecting layer of aluminum is usually added on the hologram recording layer.

It is possible to print holograms directly into steel using a sheet explosive charge to create the required surface relief.

Applications

Data storage

Holography can be put to a variety of uses other than recording images. *Holographic data storage* is a technique that can store information at high density inside crystals or photopolymers. The ability to store large amounts of information in some kind of media is of great importance, as many electronic products incorporate storage devices. As current storage techniques such as Blu-ray Disc reach the limit of possible data density (due to the diffraction-limited size of the writing beams), holographic storage has the potential to become the next generation of popular storage media.The advantage of this type of data storage is that the volume of the recording media is used instead of just the surface. Currently available SLMs can produce about 1000 different images a second at 1024×1024-bit resolution. With the right type of media (probably polymers rather than something like $LiNbO_3$), this would result in about 1 gigabit per second writing speed. Read speeds can surpass this and experts believe 1-terabit per second readout is possible.

In 2005, companies such as Optware and Maxell have produced a 120 mm disc that uses a holographic layer to store data to a potential 3.9 TB, which they plan to market under the name Holographic Versatile Disc. Another company, InPhase Technologies, is developing a competing format. While many holographic data storage models have used "page-based" storage, where each recorded hologram holds a large amount of data, more recent research into using submicrometre-sized "microholograms" has resulted in several potential 3D optical data storage solutions. While this approach to data storage can not attain the high data rates of page-based storage, the tolerances, technological hurdles, and cost of producing a commercial product are significantly lower.

Security

UBS Kinebar gold bars use holograms as a security measure

Security holograms are very difficult to forge because they are replicated from a master hologram which requires expensive, specialized and technologically advanced equipment. They are used widely in many currencies such as the Brazilian real 20 note, British pound 5/10/20 notes, Estonian kroon 25/50/100/500 notes, Canadian dollar 5/10/20/50/100 notes, Euro 5/10/20/50/100/200/500 notes, South Korean won 5000/10000/50000 notes, Japanese yen 5000/10000 notes, etc. They are also used in credit and bank cards as well as passports, ID cards, books, DVDs, and sports equipment.

Art

Early on artists saw the potential of holography as a medium and gained access to science laboratories to create their work. Holographic art is often the result of collaborations between scientists and artists, although some holographers would regard themselves as both an artist and scientist.

Salvador Dalí claimed to have been the first to employ holography artistically. He was certainly the first and best-known surrealist to do so, but the 1972 New York exhibit of Dalí holograms had been preceded by the holographic art exhibition which was held at the Cranbrook Academy of Art in Michigan in 1968 and by the one at the Finch College gallery in New York in 1970, which attracted national media attention.

During the 1970s a number of arts studios and schools were established, each with their particular approach to holography. Notably there was the San Francisco School of holography established by Lloyd Cross, The Museum of Holography in New York founded by Rosemary (Possie) H. Jackson, the Royal College of Art in London and the Lake Forest College Symposiums organised by Tung Jeong (T.J.). None of these studios still exist, however there is the Center for the Holographic Arts in New York and the HOLOcenter in Seoul which offer artists a place to create and exhibit work.

During the eighties many artists who worked with holography helped the diffusion of this so called "new medium" in the art world, artists like Harriet Casdin-Silver, USA, Dieter Jung, Germany, Moysés Baumstein, Brazil. Each one searching for a proper "language" to use with the tri-dimensional work, avoiding the simple holographic reproduction of an scuplture or object. For instance in Brazil many concrete poets (Augusto de Campos, Décio Pignatari, Julio Plaza and José Wagner Garcia, associated with Moysés Baumstein) found in the holography a way to express themselves and to renew the Concrete Poetry (or Shape Poetry).

A small but active group of artists still use holography as their main medium and many more artists integrate holographic elements into their work. Some are associated with novel holographic techniques, for example, artist Matt Brand employed computational mirror design to eliminate image distortion from specular holography.

The MIT Museum and Jonathan Ross both have extensive collections of holography and on-line catalogues of art holograms.

Hobbyist use

"Peace Within Reach" a Denisyuk DCG hologram by amateur Dave Battin

Since the beginning of holography, experimenters have explored the uses of holography. Starting in 1971 Lloyd Cross started the San Francisco School of Holography and started to teach amateurs the methods of making holograms with inexpensive equipment. This method relied on the use of a large table of deep sand to hold the optics rigid and damp vibrations that would destroy the image.

Many of these holographers would go on to produce art holograms. In 1983, Fred Unterseher published the Holography Handbook, a remarkably easy to read description of making holograms at home. This brought in a new wave of holographers and gave simple methods to use the then available AGFA silver halide recording materials.

In 2000 Frank DeFreitas published the Shoebox Holography Book and introduced using inexpensive laser pointers to countless hobbyists. This was a very important development for amateurs as the cost for a 5 mW laser dropped from $1200 to $5 as semiconductor laser diodes reached mass market. Now there are hundreds to thousands of amateur holographers worldwide.

In 2006 a large number of surplus Holography Quality Green Lasers (Coherent C315) became available and put Dichromated Gelatin (DCG) within the reach of the amateur holographer. The holography community was surprised at the amazing sensitivity of DCG to green light. It had been assumed that the sensitivity would be non existent. Jeff

Blyth responded with the G307 formulation of DCG to increase the speed and sensitivity to these new lasers.

Many film suppliers have come and gone from the silver halide market. While more film manufactures have filled in the voids, many amateurs are now making their own film. The favorite formulations are Dichromated Gelatin, Methylene Blue Sensitised Dichromated Gelatin and Diffusion Method Silver Halide preparations. Jeff Blyth has published very accurate methods for making film in a small lab or garage.

A small group of amateurs are even constructing their own pulsed lasers to make holograms of moving objects.

Holographic interferometry

Holographic interferometry (HI) is a technique which enables static and dynamic displacements of objects with optically rough surfaces to be measured to optical interferometric precision (i.e. to fractions of a wavelength of light). It can also be used to detect optical path length variations in transparent media, which enables, for example, fluid flow to be visualized and analyzed. It can also be used to generate contours representing the form of the surface.

It has been widely used to measure stress, strain, and vibration in engineering structures.

Interferometric microscopy

The hologram keeps the information on the amplitude and phase of the field. Several holograms may keep information about the same distribution of light, emitted to various directions. The numerical analysis of such holograms allows one to emulate large numerical aperture which, in turn, enables enhancement of the resolution of optical microscopy. The corresponding technique is called interferometric microscopy. Recent achievements of interferometric microscopy allow one to approach the quarter-wavelength limit of resolution.

As sensors or biosensors

The hologram is made with a modified material that interacts with certain molecules generating a change in the fringe periodicity or refractive index, therefore, the color of the holographic reflection.

Holographic sensor

A holographic sensor is a device that comprises a hologram embedded in a smart material that detects certain molecules or metabolites. This detection is usually a chemical interaction that is transduced as a change in one of the properties of the holographic reflection (as in the Bragg reflector), either refractive index or spacing between the holographic fringes. The specificity of the sensor can be controlled by adding molecules in the polymer film that selectively interact with the molecules of interest.

A holographic sensor aims to integrate the sensor component, the transducer and the display in one device for fast reading of molecular concentrations based in colorful reflections or wavelengths.

Certain molecules that mimic biomolecule active sites or binding sites can be incorporated into the polymer that forms the holographic film in order to make the holographic sensors selective and/or sensitive to certain medical important molecules like glucose, etc.

The holographic sensors can be read from a fair distance because the transducer element is light that has been refracted and reflected by the holographic grating embedded in the sensor. Therefore they can be used in industrial applications where non-contact with the sensor is required.

Metabolites

Some of the metabolites detected by a holographic sensor are:

- Hydrocarbons
    - VOCs
    - Gases
- Glucose
- Water content
- Lactate and other biomolecules
- Protons (pH sensor)
- Metal ions

Dynamic holography

In static holography, recording, developing and reconstructing occur sequentially and a permanent hologram is produced.

There also exist holographic materials which do not need the developing process and can record a hologram in a very short time. This allows one to use holography to perform some simple operations in an all-optical way. Examples of applications of such real-time holograms include phase-conjugate mirrors ("time-reversal" of light), optical cache memories, image processing (pattern recognition of time-varying images), and optical computing.

The amount of processed information can be very high (terabit/s), since the operation is performed in parallel on a whole image. This compensates for the fact that the recording time, which is in the order of a microsecond, is still very long compared to the processing time of an electronic computer. The optical processing performed by a dynamic hologram is also much less flexible than electronic processing. On one side one has to perform the operation always on the whole image, and on the other side the operation a hologram can perform is basically either a multiplication or a phase conjugation. But remember that in optics, addition and Fourier transform are already easily performed in linear materials, the second simply by a lens. This enables some applications like a device that compares images in an optical way.

The search for novel nonlinear optical materials for dynamic holography is an active area of research. The most common materials are photorefractive crystals, but also in semiconductors or semiconductor heterostructures (such as quantum wells), atomic vapors and gases, plasmas and even liquids it was possible to generate holograms.

A particularly promising application is optical phase conjugation. It allows the removal of the wavefront distortions a light beam receives when passing through an aberrating medium, by sending it back through the same aberrating medium with a conjugated phase. This is useful for example in free-space optical communications to compensate for atmospheric turbulence (the phenomenon that gives rise to the twinkling of starlight).

Non-optical applications

In principle, it is possible to make a hologram for any wave.

Electron holography is the application of holography techniques to electron waves rather than light waves. Electron holography was invented by Dennis Gabor to improve the resolution and avoid the aberrations of the transmission electron microscope. Today it is commonly used to study electric and magnetic fields in thin films, as magnetic and electric fields can shift the phase of the interfering wave passing through the sample. The principle of electron holography can also be applied to interference lithography.

Acoustic holography is a method used to estimate the sound field near a source by measuring acoustic parameters away from the source via an array of pressure and/or particle velocity transducers. Measuring techniques included within acoustic holography are becoming increasingly popular in various fields, most notably those of transportation, vehicle and aircraft design, and NVH. The general idea of acoustic holography has led to different versions such as near-field acoustic holography (NAH) and statistically optimal near-field acoustic holography (SONAH). For audio rendition, the wave field synthesis is the most related procedure.

Atomic holography has evolved out of the development of the basic elements of atom optics. With the Fresnel diffraction lens and atomic mirrors atomic holography follows a natural step in the development of the physics (and applications) of atomic beams. Recent developments including atomic mirrors and especially ridged mirrors have provided the tools necessary for the creation of atomic holograms, although such holograms have not yet been commercialized.

Other applications

Holographic scanners are in use in post offices, larger shipping firms, and automated conveyor systems to determine the three-dimensional size of a package. They are often used in tandem with checkweighers to allow automated pre-packing of given volumes, such as a truck or pallet for bulk shipment of goods.

Chapter- 2

Holographic Data Storage and Security Hologram

Holographic data storage

Holographic data storage is a potential replacement technology in the area of high-capacity data storage currently dominated by magnetic and conventional optical data storage. Magnetic and optical data storage devices rely on individual bits being stored as distinct magnetic or optical changes on the surface of the recording medium. Holographic data storage overcomes this limitation by recording information throughout the volume of the medium and is capable of recording multiple images in the same area utilizing light at different angles.

Additionally, whereas magnetic and optical data storage records information a bit at a time in a linear fashion, holographic storage is capable of recording and reading millions of bits in parallel, enabling data transfer rates greater than those attained by optical storage.

Recording data

Holographic data storage captures information using an non optical interference pattern within a thick, photosensitive optical material. Light from a single laser beam is divided into two separate optical patterns of dark and light pixels. By adjusting the reference beam angle, wavelength, or media position, a multitude of holograms (theoretically, several thousand) can be stored on a single volume. The theoretical limits for the storage density of this technique is approximately several tens of Terabytes (1 terabyte = 1024 gigabytes) per cubic centimeter. In 2006, InPhase Technologies published a white paper reporting an achievement of 500 Gb/in^2. From this figure we can deduce that a regular disk (with 4 cm radius of writing area) could hold up to a maximum of 3895.6Gb

Reading data

The stored data is read through the reproduction of the same reference beam used to create the hologram. The reference beam's light is focused on the photosensitive material, illuminating the appropriate interference pattern, the light diffracts on the interference pattern, and projects the pattern onto a detector. The detector is capable of reading the data in parallel, over one million bits at once, resulting in the fast data transfer rate. Files on the holographic drive can be accessed in less than 200 milliseconds.

Longevity

Holographic data storage can provide companies a method to preserve and archive information. The write-once, read many (WORM) approach to data storage would ensure content security, preventing the information from being overwritten or modified. Manufacturers believe this technology can provide safe storage for content without degradation for more than 50 years, far exceeding current data storage options. Counterpoints to this claim are that the evolution of data reader technology changes every ten years; therefore, being able to store data for 50–100 years would not matter if you could not read or access it. However, a storage method that works very well could be around longer before needing a replacement; plus, with the replacement, the possibility of backwards-compatibility exists, similar to how DVD technology is backwards-compatible with CD technology.

Terms used

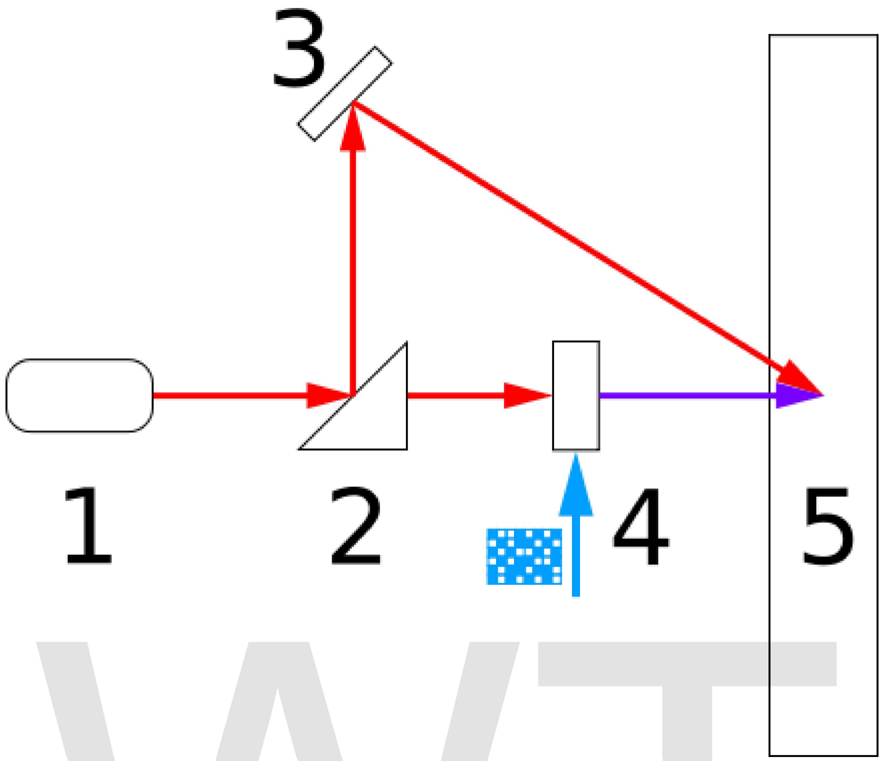
Sensitivity refers to the extent of refractive index modulation produced per unit of exposure. Diffraction efficiency is proportional to the square of the index modulation times the effective thickness.

The **dynamic range** determines how many holograms may be multiplexed in a single volume data.

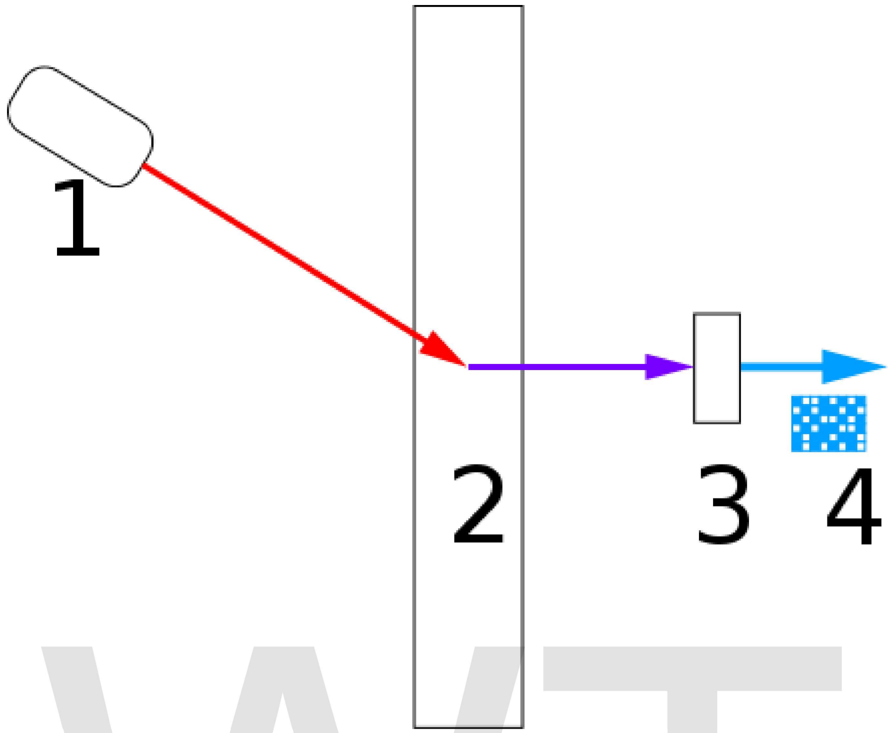
Spatial light modulators (SLM) are pixelated input devices (liquid crystal panels), used to imprint the data to be stored on the object beam.

Technical aspects

Like other media, holographic media is divided into write once (where the storage medium undergoes some irreversible change), and rewritable media (where the change is reversible). Rewritable holographic storage can be achieved via the photorefractive effect in crystals:



- Mutually coherent light from two sources creates an interference pattern in the media. These two sources are called the reference beam and the signal beam.
- Where there is constructive interference the light is bright and electrons can be promoted from the valence band to the conduction band of the material (since the light has given the electrons energy to jump the energy gap). The positively charged vacancies they leave are called holes and they must be immobile in rewritable holographic materials. Where there is destructive interference, there is less light and few electrons are promoted.
- Electrons in the conduction band are free to move in the material. They will experience two opposing forces that determine how they move. The first force is the coulomb force between the electrons and the positive holes that they have been promoted from. This force encourages the electrons to stay put or move back to where they came from. The second is the pseudo-force of diffusion that encourages them to move to areas where electrons are less dense. If the coulomb forces are not too strong, the electrons will move into the dark areas.
- Beginning immediately after being promoted, there is a chance that a given electron will recombine with a hole and move back into the valence band. The faster the rate of recombination, the fewer the number of electrons that will have the chance to move into the dark areas. This rate will affect the strength of the hologram.
- After some electrons have moved into the dark areas and recombined with holes there, there is a permanent space charge field between the electrons that moved to the dark spots and the holes in the bright spots. This leads to a change in the index of refraction due to the electro-optic effect.

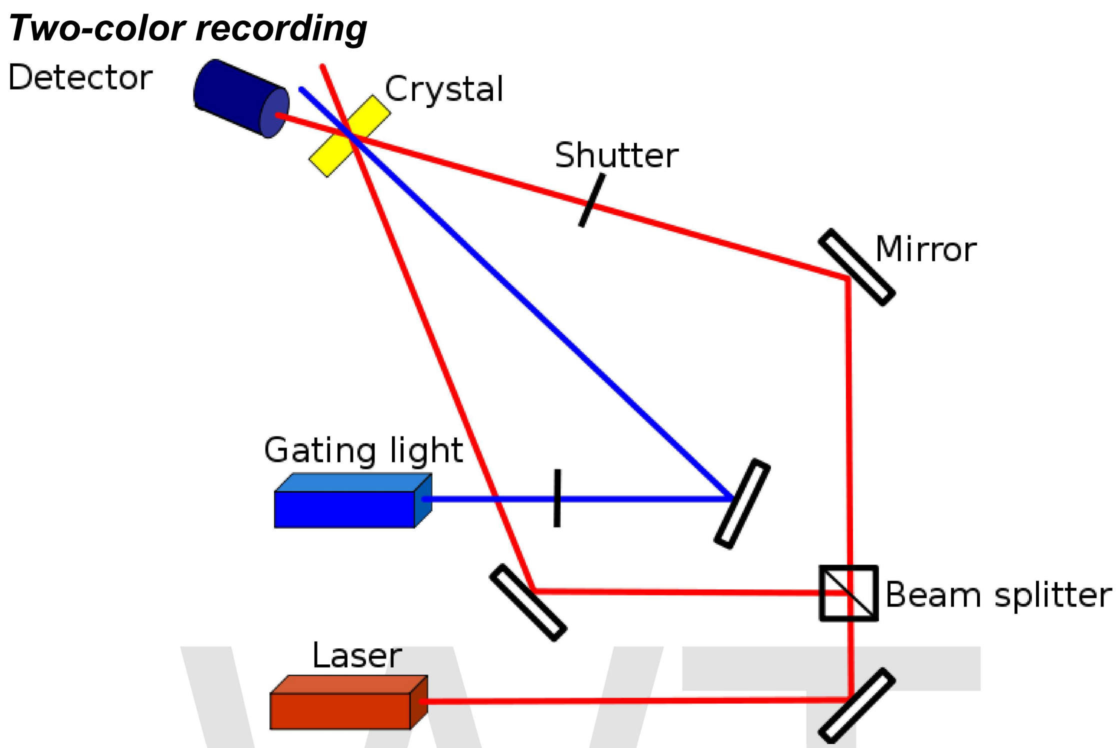


When the information is to be retrieved or read out from the hologram, only the reference beam is necessary. The beam is sent into the material in exactly the same way as when the hologram was written. As a result of the index changes in the material that were created during writing, the beam splits into two parts. One of these parts recreates the signal beam where the information is stored. Something like a CCD camera can be used to convert this information into a more usable form.

Holograms can theoretically store one bit per cubic block the size of the wavelength of light in writing. For example, light from a helium-neon laser is red, 632.8 nm wavelength light. Using light of this wavelength, perfect holographic storage could store 4 gigabits per cubic millimetre. In practice, the data density would be much lower, for at least four reasons:

- The need to add error-correction
- The need to accommodate imperfections or limitations in the optical system
- Economic payoff (higher densities may cost disproportionately more to achieve)
- Design technique limitations—a problem currently faced in magnetic Hard Drives wherein magnetic domain configuration prevents manufacture of disks that fully utilize the theoretical limits of the technology.

Unlike current storage technologies that record and read one data bit at a time, holographic memory writes and reads data in parallel in a single flash of light.



Set up for holographic recording

For two-color holographic recording, the reference and signal beam fixed to a particular wavelength (green, red or IR) and the sensitizing/gating beam is a separate, shorter wavelength (blue or UV). The sensitizing/gating beam is used to sensitize the material before and during the recording process, while the information is recorded in the crystal via the reference and signal beams. It is shone intermittently on the crystal during the recording process for measuring the diffracted beam intensity. Readout is achieved by illumination with the reference beam alone. Hence the readout beam with a longer wavelength would not be able to excite the recombined electrons from the deep trap centers during readout, as they need the sensitizing light with shorter wavelength to erase them.

Usually, for two-color holographic recording, two different dopants are required to promote trap centers, which belong to transition metal and rare earth elements and are sensitive to certain wavelengths. By using two dopants, more trap centers would be created in the Lithium niobate crystal. Namely a shallow and a deep trap would be created. The concept now is to use the sensitizing light to excite electrons from the deep trap farther from the valence band to the conduction band and then to recombine at the shallow traps nearer to the conduction band. The reference and signal beam would then be used to excite the electrons from the shallow traps back to the deep traps. The information would hence be stored in the deep traps. Reading would be done with the reference beam since the electrons can no longer be excited out of the deep traps by the long wavelength beam.

==Effect of annealingdoubly doped $LiNbO_3$ crystal there exists an optimum oxidation/reduction state for desired performance. This optimum depends on the doping levels of shallow and deep traps as well as the annealing conditions for the crystal samples. This optimum state generally occurs when 95 – 98% of the deep traps are filled. In a strongly oxidized sample holograms cannot be easily recorded and the diffraction efficiency is very low. This is because the shallow trap is completely empty and the deep trap is also almost devoid of electrons. In a highly reduced sample on the other hand, the deep traps are completely filled and the shallow traps are also partially filled. This results in very good sensitivity (fast recording) and high diffraction efficiency due to the availability of electrons in the shallow traps. However during readout, all the deep traps get filled quickly and the resulting holograms reside in the shallow traps where they are totally erased by further readout. Hence after extensive readout the diffraction efficiency drops to zero and the hologram stored cannot be fixed.

Development and marketing

At the National Association of Broadcasters 2005 (NAB) convention in Las Vegas, InPhase conducted public demonstrations of the world's first prototype of a commercial storage device at the Maxell Corporation of America booth.

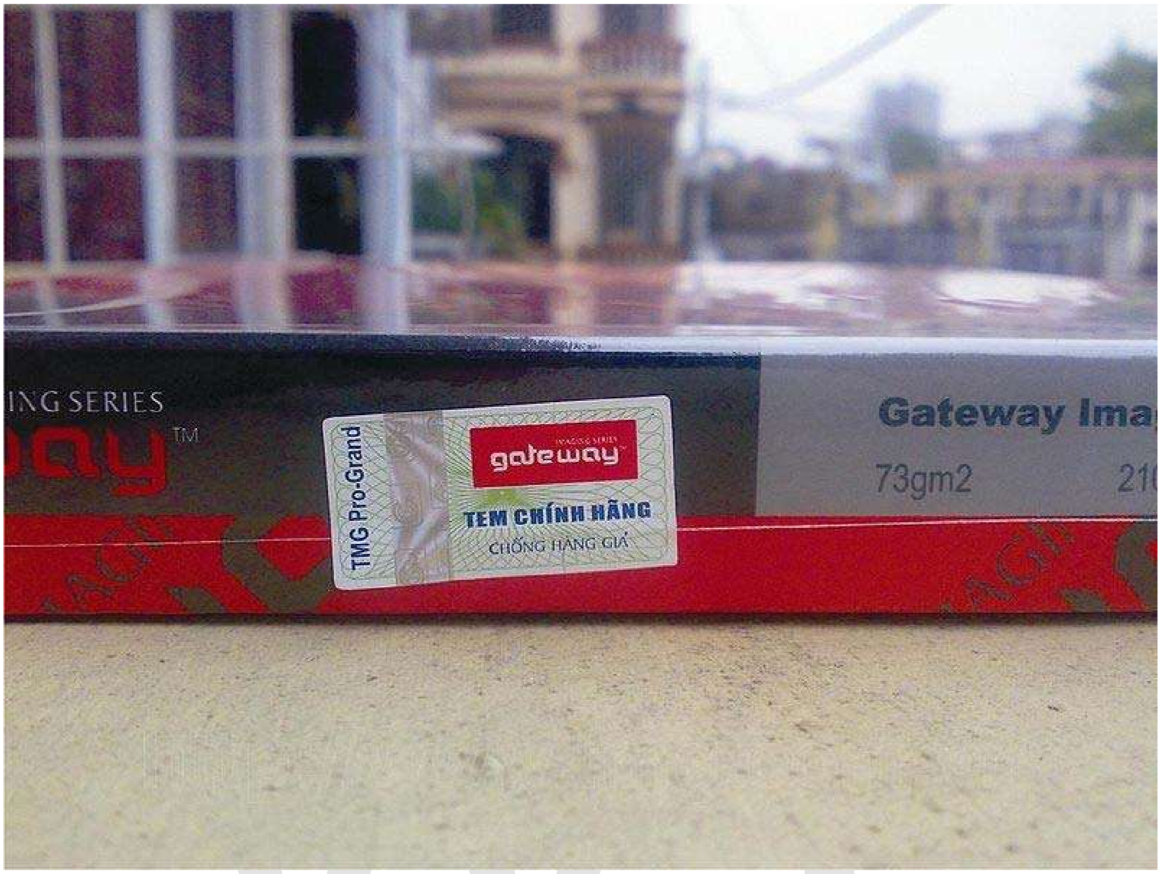
The three main companies involved in developing holographic memory, as of 2002, were InPhase and Polaroid spinoff Aprilis in the United States, and Optware in Japan. Although holographic memory has been discussed since the 1960s, and has been touted for near-term commercial application at least since 2001, it has yet to convince critics that it can find a viable market. As of 2002, planned holographic products did not aim to compete head to head with hard drives, but instead to find a market niche based on virtues such as speed of access.

InPhase Technologies, after several announcements in 2006 and 2007—and successive delays—that it would soon be introducing a flagship product (which amounted to "vaporware"), went out of business in February 2010 and had its assets seized by the state of Colorado for back taxes. The company had reportedly gone through $100 million but the lead investor was unable to raise more capital.

In April 2009, GE Global Research demonstrated their own holographic storage material that could allow for discs that utilize similar read mechanisms as those found on Blu-ray Disc players.

Security hologram

A hologram on a Nokia mobile phone battery. This is intended to show the battery is 'original Nokia' and not a cheaper imitation.



A hologram label on a paper box for security

Security holograms are very difficult to forge because they are replicated from a master hologram which requires expensive, specialized and technologically advanced equipment. They are used widely in several banknotes around the world, in particular those that are of high denominations. They are also used in passports, credit and bank cards as well as quality products.

Holograms are classified into different types with reference to the degree of level of optical security incorporated in them during the process of master origination. The different classifications are described below:

2D / 3D "hologram" images

These are by far the most common type of hologram - and in fact they are not holograms in any true sense of the words. The term "hologram" has taken on a secondary meaning due to the widespread use of a multilayer image on credit cards and driver licenses. This type of "hologram" consists of two or more images stacked in such a way that each is alternately visible depending upon the angle of perspective of the viewer. The technology here is similar to the technology used for the past 50 years to make red safety night reflectors for bicycles, trucks, and cars. These holograms (and therefore the artwork of these holograms) may be of two layers (i.e. with a background and a foreground) or three layers (with a background, a middle ground and a foreground). The matter of the middle ground in the case of the two-layer holograms are usually superimposed over the matter of the background of the hologram. These holograms display a unique multilevel, multi-colour effect. These images have one or two levels of flat graphics "floating" above or at the surface of the hologram. The matter in the background appears to be under or behind the hologram, giving the illusion of depth.

Dot matrix

These holograms have a maximum resolution of 10 micrometres per optical element and are produced on specialized machines making forgery difficult and expensive. To design optical elements, several algorithms are used to shape scattered radiation patterns.

Electron-beam lithography

These types of hologram are originated using highly sophisticated and very expensive electron-beam lithography system and this is the latest technology in the world at present. This kind of technology allows the creation of surface holograms with a resolution of up to 0.1 micrometres (254,000 dpi). This technique requires development of various algorithms for designing optical elements that shapes scattered radiation patterns. This type of hologram offers features like the viewing of four lasers at a single point, 2D/3D raster text, switch effects, 3D effects, concealed images, laser readable text and true colour images.

The various kinds of features possible in security holograms are mentioned below:

Concealed images

These usually take the form of very thin lines and contours. Concealed images can be seen at large angle light diffraction, and at one particular angle only.

Guilloché pattern (high resolution line patterns)

These are sets of thin lines of a complicated geometry (guilloché patterns) drawn with high resolution. The technology allows continuous visual changes of colour along each separated lines.

Kinetic images

They can be seen when the conditions of hologram observations are being changed. Turning or inclining the hologram allows the movements of certain features of the image to be studied.

Microtexts or nanotexts

Dot matrix holograms are capable of embedding microtext at various sizes. There are three types of microtexts in holograms: high contrast microtexts of size 50 – 150 micrometres; diffractive grating filled microtexts of size 50 – 150 micrometres low contrast microtexts. Microtexts of sizes smaller than 50 micrometres are referred to as nanotext. Nanotext with sizes of less than 50 micrometres can be observed with a microscope only.

CLR (Covert Laser Readable) image

Dot matrix holograms also support CLR imagery, where a simple laser device may be used to verify the hologram's authenticity. Computing CLR images is a complicated mathematical task that involves solving ill-posed problems. There are two types of CLR: Dynamic CLR and Multigrade CLR. Dynamic CLR is a set of CLR fragments that produce animated images on the screen as the control device moves along the hologram surface. Multigrade CLR images produce certain images on the screen of the controlling device, which differ in the first and minus first orders of laser light diffraction. As a variant, a hidden image which is both negative and positive, in plus one and minus one order respectively, may be created.

Computer-synthesized 2D/3D and 3D images

This technology allows 2D / 3D images to be combined with other security features (microtexts, concealed images, CLR etc.) - this combination effect cannot be achieved using any other traditional technologies of origination.

True colour images

True colour images are very effective decorative pictures. When synthesized by computer, they may include microtexts, hidden images, and other security features, yielding attractive, high-security holograms.

Chapter- 3

Volumetric Display

A **volumetric display device** is a graphical display device that forms a visual representation of an object in three physical dimensions, as opposed to the planar image of traditional screens that simulate depth through a number of different visual effects. One definition offered by pioneers in the field is that volumetric displays create 3-D imagery via the emission, scattering, or relaying of illumination from well-defined regions in (x,y,z) space. Though there is no consensus among researchers in the field, it may be reasonable to admit holographic and highly multiview displays to the volumetric display family if they do a reasonable job of projecting a three-dimensional light field within a volume.

Most, if not all, volumetric 3-D displays are autostereoscopic; that is, they create 3-D imagery visible to the unaided eye. Note that some display technologists reserve the term “autostereoscopic” for flat-panel spatially-multiplexed parallax displays, such as lenticular-sheet displays. However, nearly all 3-D displays other than those requiring headwear, e.g. stereo goggles and stereo head-mounted displays, are autostereoscopic. Therefore, a very broad group of display architectures are properly deemed autostereoscopic.

Volumetric 3-D displays embody just one family of 3-D displays in general. Other types of 3-D displays are: stereograms / stereoscopes, view-sequential displays, electro-holographic displays, parallax "two view" displays and parallax panoramagrams (which are typically spatially-multiplexed systems such as lenticular-sheet displays and parallax barrier displays), re-imaging systems, and others.

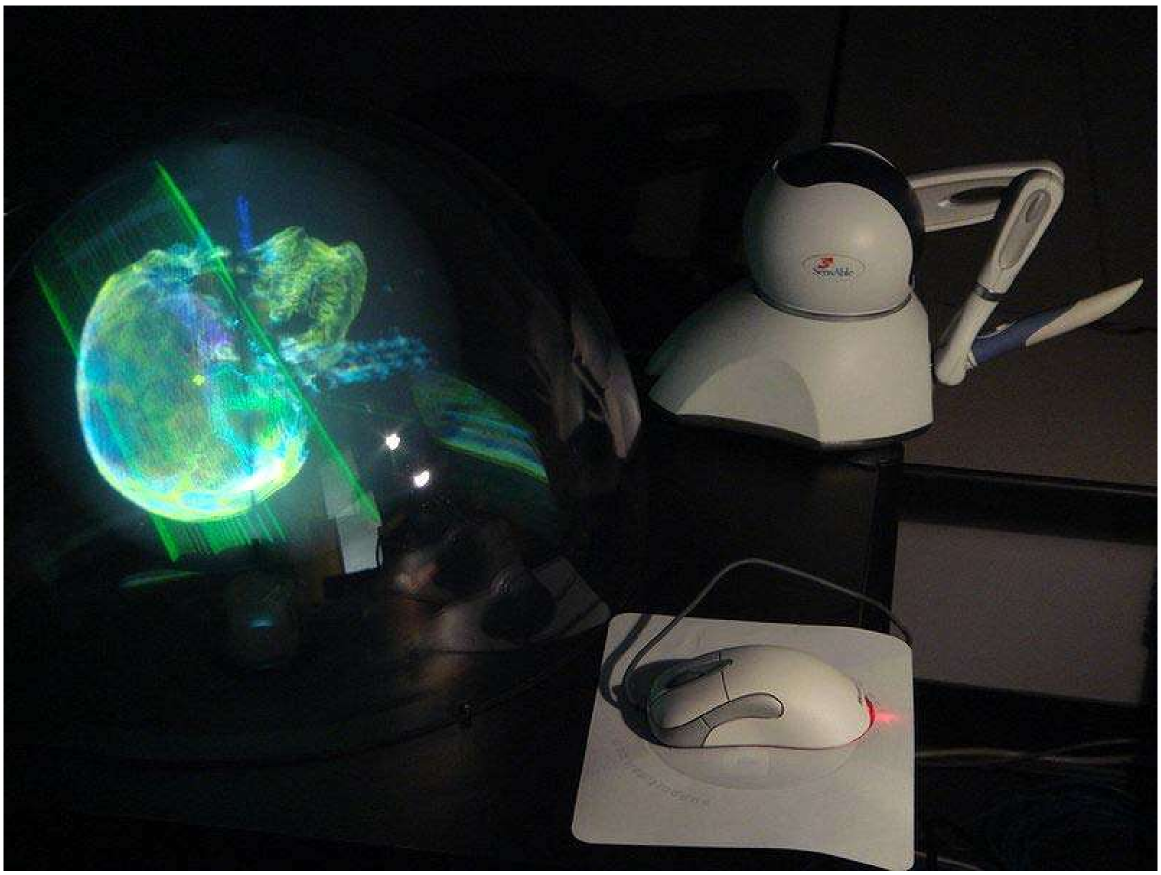
Although first postulated in 1912, and a staple of science fiction, volumetric displays are still under development, and have yet to reach the general population. With a variety of systems proposed and in use in small quantities — mostly in academia and various research labs — volumetric displays remain accessible only to academics, corporations, and the military.

Types

Many different attempts have been made to extend the dynamic 2D representation of the cathode ray tube to three dimensions. There is no officially accepted "taxonomy" of the variety of volumetric displays, an issue which is complicated by the many permutations of their characteristics. For example, illumination within a volumetric display can either reach the eye directly or via an intermediate surface; likewise, the surface, which need not be tangible, can undergo motion such as reciprocation or rotation. One categorization is as follows:

Swept-volume display

Swept-surface (or "swept-volume") volumetric 3-D displays rely on the human persistence of vision to fuse a time-series of regions of the ultimate 3-D region into a single 3-D image. A variety of swept-volume displays have been created.



Every second, approximately 6,000 planar cross-sections of a 3-D volume are projected onto a spinning diffuser in the Perspecta volumetric 3-D display (made by the former Actuality Systems, Inc.). This is a 10" (25 cm)-diameter volume-filling image of an external beam radiation oncolgy image for brain cancer.

For example, the 3-D scene is computationally decomposed into a series of "slices," which can be rectangular, disc-shaped, or helical cross-sectioned, whereupon they are projected onto or from a display surface undergoing motion. The image on the 2D surface (created by projection onto the surface, LEDs embedded in the surface, or other techniques) changes as the surface rotates. Due to the persistence of vision humans perceive a volume of light. The display surface can be reflective, transmissive, or a combination of both.

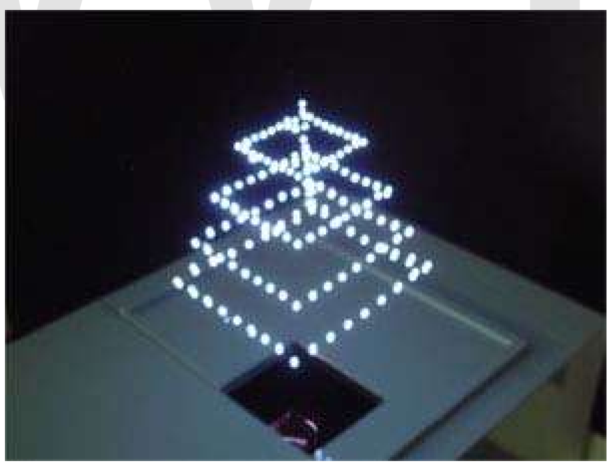
Another type of 3-D display which is a candidate member of the class of swept-volume 3-D displays is the varifocal mirror architecture. One of the first references to this type of system is in 1966, in which a vibrating mirrored drumhead re-images a series of patterns from a high frame rate 2-D image source, such as a vector display, to a corresponding set of depth surfaces.

Static volume

So-called "static volume" volumetric 3-D displays create imagery without any macroscopic moving parts in the image volume. It is unclear if the rest of the system must remain stationary for membership in this display class to be viable.

This is probably the most 'direct' form of volumetric display. In the simplest case, an addressable volume of space is created out of active elements that are transparent in the *off* state but are either opaque or luminous in the *on* state. When the elements or voxels are activated they show a solid pattern within the space of the display.

Several static-volume volumetric 3-D displays use laser light to encourage visible radiation in a solid, liquid, or gas. For example, some researchers have relied on two-step upconversion within a rare earth-doped material when illuminated by intersecting infrared laser beams of the appropriate frequencies.



A pulsed laser creates points of glowing plasma in air

Another technique uses a focused pulsed infrared laser (about 100 pulses per second; each lasting a nanosecond) to create balls of glowing plasma at the focal point in normal air. The focal point is directed by two moving mirrors and a sliding lens, allowing it to draw shapes in the air. Each pulse creates a popping sound, so the device crackles as it runs. Currently it can generate dots anywhere within a cubic metre. It is thought that the device could be scaled up to any size, allowing for 3D images to be generated in the sky.

Candidates

Parallax panoramagrams, such as parallax barrier displays, generate an approximation of a desired 3-D light field. For a sufficient angular density of "view" directions, the synthesized 3-D light field becomes nearly equivalent to a volumetric image. Some researchers state that even a flat-panel 3-D display that projects over 30 views within a 30-degree horizontal field of view evokes an accommodation response in the viewer. Therefore, multiview displays with a high angular view density might be rightful members of the class of volumetric 3-D displays.

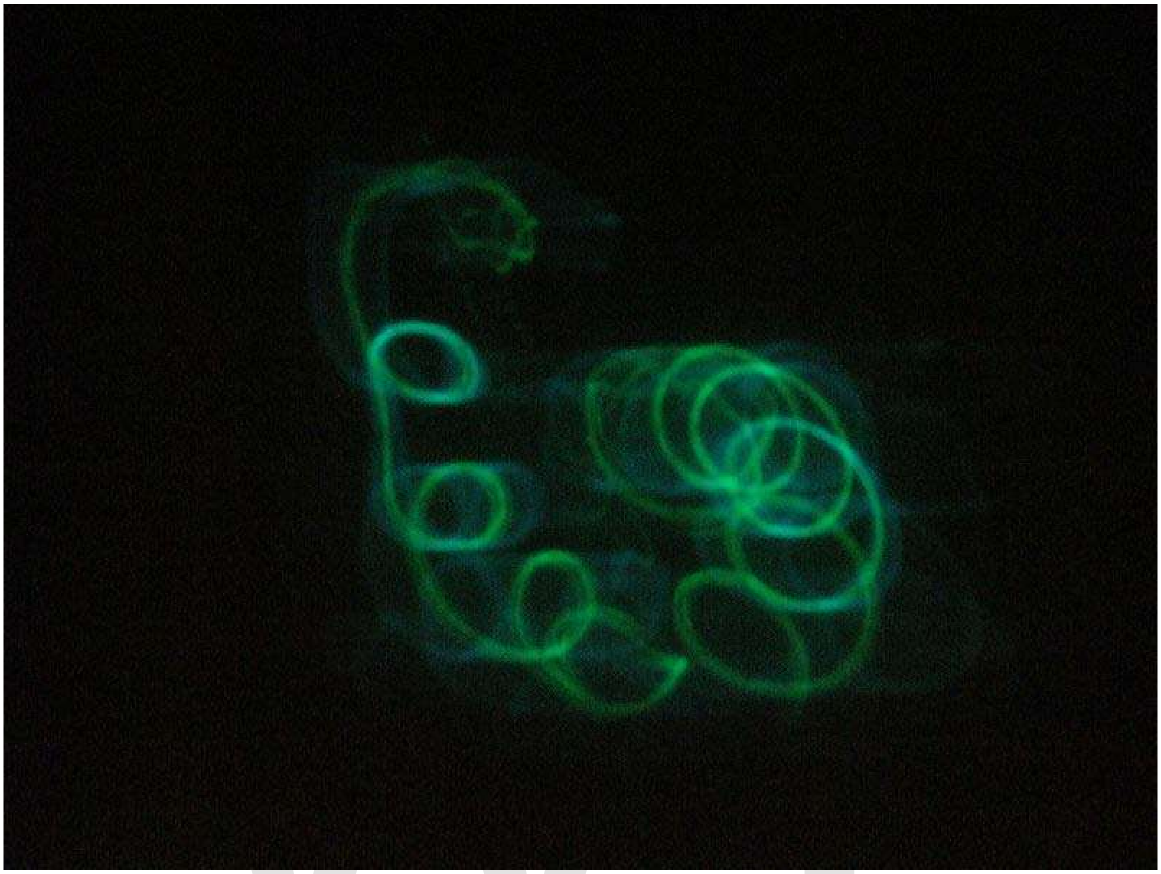
The realistic imagery of holograms and electro-holographic displays make them contenders for membership in the class of volumetric 3-D displays, as well.

Human-computer interfaces

The unique properties of volumetric displays, which may include: 360-degree viewing, agreement of converge and accommodation cues, and their inherent "three-dimensionality," enable new user interface techniques. There is recent work investigating the speed and accuracy benefits of volumetric displays (Van Orden et al, 2000), new graphical user interfaces (Grossman et al, 2004), and medical applications enhanced by volumetric displays (Med., 2005; Wang et al, 2005)...

Also, software platforms exist which deliver native and legacy 2-D and 3-D content to volumetric displays (Chun et al, 2005).

Artistic use



Hologlyphics: Artistic use of Volumetric Displays, involving volumetric movies and music

An artform called Hologlyphics has been explored since 1994, combining elements of holography, music, video synthesis, visionary film, sculpture and improvisation. Volumetric movies have been shown to live audiences at film festivals, art galleries and music events. Multiple Volumetric Displays and multi-loudspeaker arrays surround an audience. The movies are shown in conjunction with music, either live or recorded with the volumetric animations.

The original intent was to combine Holography with Music, and finally Volumetric Displays were settled on as an artistic medium. Many traditional film & video special effects have been adapted to Hologlyphic Movies, plus many more special effects unique to Volumetric Displays have been developed. These include volumetric wipe effects, raster bending, morphing, kaleidoscope & mirroring effects, experimental rotations, spatial warping effects and image sequencing.

The Hologlyphic movies can also be performed in real-time, like a video synthesizer, controlled by musical keyboards, motion sensors, control panels, and acoustic instruments. The image generation system is mostly digital, but some of the original image generators and processors were analog and remain in use.

Drawbacks

Known volumetric display technologies also have several drawbacks that are exhibited depending on trade-offs chosen by the system designer.

It is often claimed that volumetric displays are incapable of reconstructing scenes with viewer-position-dependent effects, such as occlusion and opacity. This is a misconception; a display whose voxels have non-isotropic radiation profiles are indeed able to depict position-dependent effects. To-date, occlusion-capable volumetric displays require two conditions: (1) the imagery is rendered and projected as a series of "views," rather than "slices," and (2) the time-varying image surface is not a uniform diffuser. For example, researchers have demonstrated spinning-screen volumetric displays with reflective and/or vertically diffuse screens whose imagery exhibits occlusion and opacity. One system (Cossairt et al, 2004; Favalora, 4 Aug. 2005) created HPO 3-D imagery with a 360-degree field of view by oblique projection onto a vertical diffuser; another (Otsuka et al, 2004) projects 24 views onto a rotating controlled-diffusion surface; and another (Tanaka et al, 2006) provides 12-view images utilizing a vertically oriented louver.

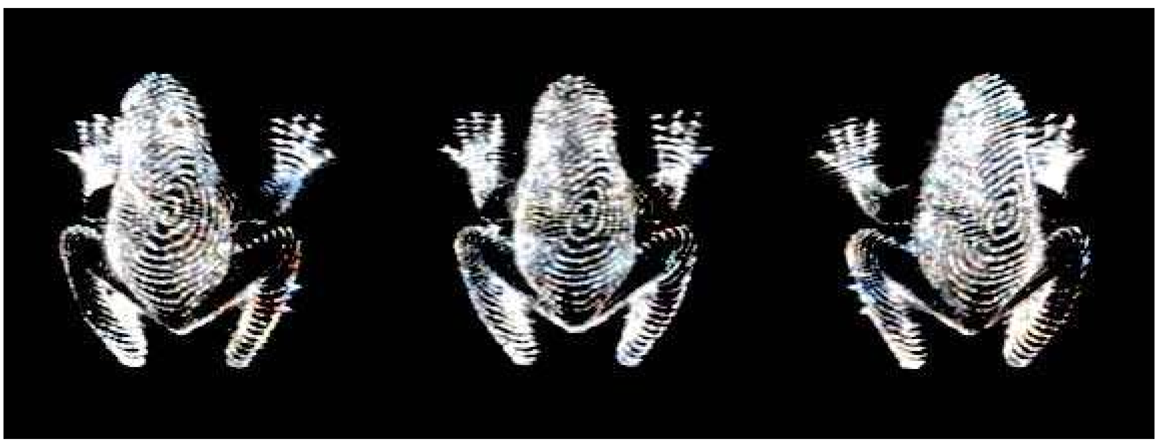
So far, the ability to reconstruct scenes with occlusion and other position-dependent effects have been at the expense of vertical parallax, in that the 3-D scene appears distorted if viewed from locations other than those the scene was generated for.

One other consideration is the very large amount of bandwidth required to feed imagery to a volumetric display. For example, a standard 24 bit per pixel, 1024×768, flat/2D display requires about 165 MB/s to be sent to the display hardware to sustain 70 frames per second, whereas a 24 bit per voxel, 1024×768×1024 (1024 "pixel layers" in the Z axis) volumetric display would need to send about three orders of magnitude more (165 GB/s) to the display hardware to sustain 70 volumes per second. As with regular 2-D video, one could reduce the bandwidth needed by simply sending fewer volumes per second and letting the display hardware repeat frames in the interim, or by sending only enough data to affect those areas of the display that need to be updated, as is the case in modern lossy-compression video formats such as MPEG. Furthermore, a 3-D volumetric display would require two to three orders of magnitude more CPU and/or GPU power beyond that necessary for 2-D imagery of equivalent quality, due at least in part to the sheer amount of data that must be created and sent to the display hardware. However, if only the outer surface of the volume is visible, the number of voxels required would be of the same order as the number of pixels on a conventional display. This would only be the case if the voxels do not have "alpha" or transparency values.

Chapter- 4

Specular Holography and Electron Holography

Specular holography



Three views of a specular hologram

Specular holography is a technique for making three dimensional imagery by controlling the motion of specularities on a two-dimensional surface. The image is made of many specularities and has the appearance of a 3D surface-stippling made of dots of light. Unlike conventional wavefront holograms, specular holograms do not depend on wave optics, photographic media, or lasers.

The principle of operation is purely one of geometric optics: A point light source produces a glint on a curved specular (shiny) surface; this glint appears to travel on the surface as the eye or light source moves. If that motion is projectively consistent with binocular disparity, the viewer will perceive --- via stereopsis --- the illusion that the glint occurs at a different depth than the surface that produces it. A specular hologram contains many such curved surfaces, all embedded in a host surface. Each produces a glint and the brain integrates the many 3D cues to produce a percept of a 3D shape.

Overview and history

Specular holography dates back to Hans Weil's attempts in the 1930s and thus has a longer history than conventional wavefront holography. It is used most often in art and optics demonstrations. Historically, it was not very successful because it produced images with severe distortion. It was not until 2008 that the correct geometry for distortion-free images was demonstrated by Matt Brand.

The earliest conception of specular holography appears to be a 1934 United Kingdom patent by Hans Weil. The patent noted that scratches in a shiny surface produce glints that are only visible to certain viewpoints, depending on the scratch orientation; this anisotropy could be exploited to produce different images for different viewers. Weil appreciated that this might be used to produce 3D imagery, but it not clear whether he knew how to do so, especially considering that modern techniques are heavily computational.

In the 1970s, Gabriel Liebermann discovered that a scratch in the shape of a circular arc produces glints whose motion is approximately consistent with binocular disparity. His 1980 artwork World Brain is made of CNC-machined semi-circular arcs that produce a holographic effect. The phenomenon was independently discovered in the 1990s by William Beatty who popularized a method of making hand-drawn holograms using a compass (drafting). This has come to be known as scratch holography.

Beatty established a connection between scratch holography and conventional wavefront holography by pointing out that a circular arc approximates a scaled-up Benton rainbow hologram of a single point. This explains why scratch hologram images are subject to distracting distortions and collapse of the depth image outside of a very narrow field of view --- circular arcs are a fairly poor approximation to rainbow hologram fringes.

Beatty also pointed out that the rainbow hologram of a single point is a rectangular section of nested parabolics. If one were to view that geometry as a 3D reflective surface under collimated light, one would observe glint motion that is consistent with horizontal parallax. An everyday example is the parabolic Fresnel mirror used in many solar cookers. On cookers with fine Fresnel patterns, the holographic image of depth-varying bar of light is readily apparent.

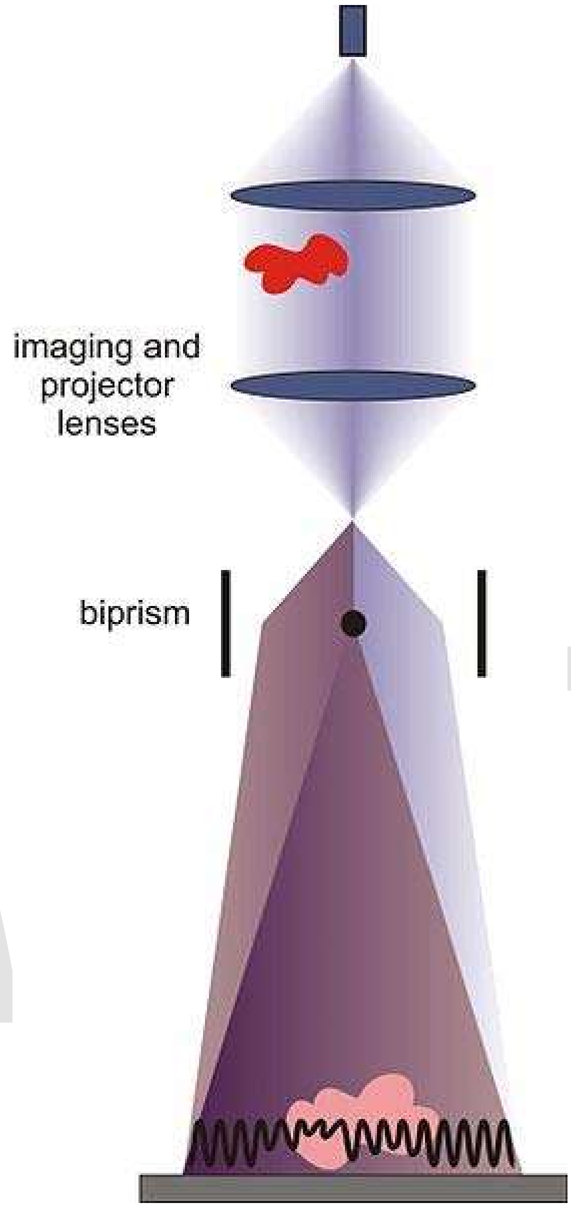
In 2008, Matt Brand demonstrated a distortion-free form of specular holography. Instead of scratches, it employs very fine curved mirrors or refractors, each computationally designed to produce distortion-free parallax over a wide field of view. Brand's method considers the bundle of light rays that must be delivered to the viewer as the viewer, light source, hologram, and holographic image move relative to each other. Through the law of reflection or Snell's law, this determines a set of differential or integral equations that relate the position and normal of each point on an optical surface. The equations specify a foliation of possible optical surfaces; the hologram is an intersection of this foliation and a thin shell that conforms to the host surface. Solar cookers represent one such foliation; scratch holograms do not, hence their distortion. One interesting property of the foliation approach is that it yields solutions for non-flat holographic surfaces and for unconventional viewing geometries. Brand has exhibited holograms with 3D scenes, animation, and ultra-wide field of view.

Electron holography

Electron holography is holography with electron waves. Dennis Gabor invented holography in 1948 when he tried to improve resolution in electron microscope. The first attempts to perform holography with electron waves were made by Haine and Muley in 1952; they demonstrated recorded with 60keV electrons holograms of zinc oxide crystals and their reconstructions at about 1nm resolution. In 1955 G. Möllenstedt and H. Düker invented biprism for electrons and recording of electron holograms in off-axis scheme became possible. Cowley has described 20 configurations for electron holography. Usually, high spatial and temporal coherence (i.e. energy spread) of electron beam are required to perform holographic measurements.

High-energy electron holography in off-axis scheme

Electron holography with high-energy electrons (80-200keV) can be realized in a transmission electron microscope (TEM) in off-axis scheme. Electron beam is split into two parts by very thin positively charged wire. Positive voltage deflects the electron waves so that they overlap and produce an interference pattern of equidistantly spaced fringes.

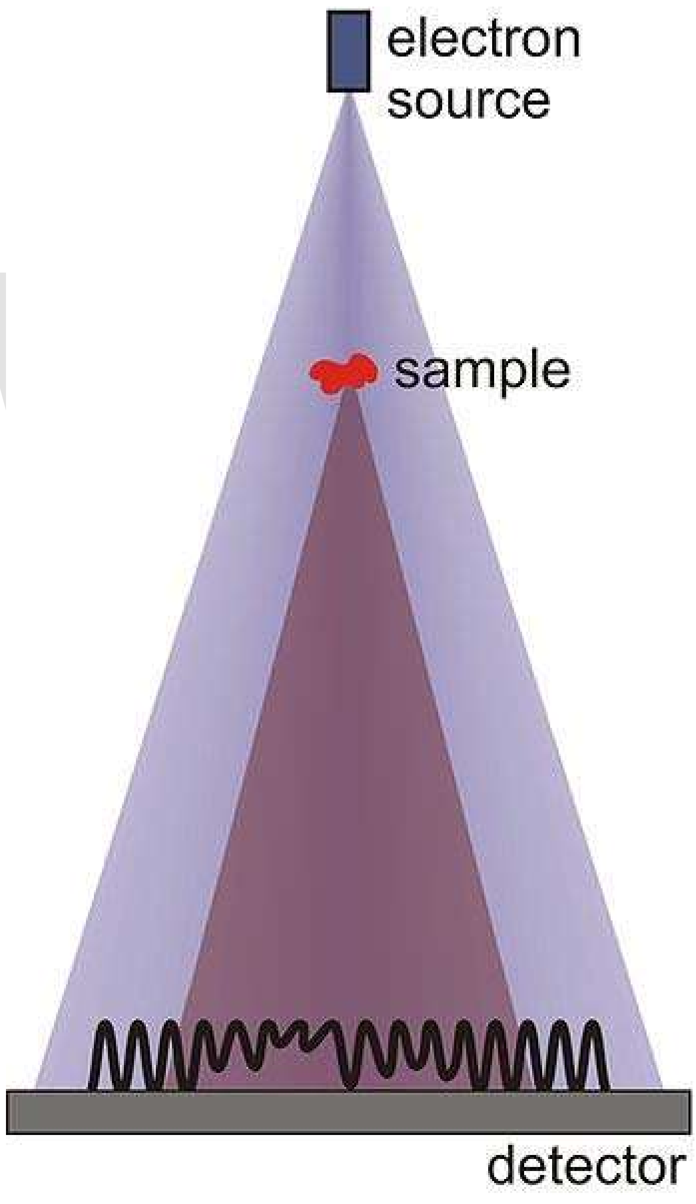


An illustration to off-axis electron holography in transmission electron microscope

Reconstruction of off-axis holograms is done numerically and it consists of two mathematical transformations. First, a Fourier transform of the hologram is performed. The resulting complex image consists of the autocorrelation (center band) and two mutually conjugated sidebands. Only one side band is selected by applying a low-pass filter (round mask) centered on the chosen side-band. The central band and the twin side-band are both set to zero. Next, the selected side-band is re-positioned to the center of the complex image and the backward Fourier-transform is applied. The resulting image in the object domain is complex-valued, and thus, the amplitude and phase distributions of the object function are reconstructed.

Electron holography in in-line scheme

Original holographic scheme by Dennis Gabor is inline scheme, which means that reference and object wave share the same optical axis. This scheme is also called *point projection holography*. An object is placed into divergent electron beam, part of the wave is scattered by the object (object wave) and it interferes with the unscattered wave (reference wave) in detector plane. The spatial coherence in in-line scheme is defined by the size of the electron source. Holography with low-energy electrons (50-1000eV) can be realized in in-line scheme.



Inline electron holography scheme

Electromagnetic fields

It is important to shield the interferometric system from electromagnetic fields, as they can induce unwanted phase-shifts due to the Aharonov-Bohm effect. Static fields will result in a fixed shift of the interference pattern. It is clear every component and sample must be properly grounded and shielded from outside noise.

Applications

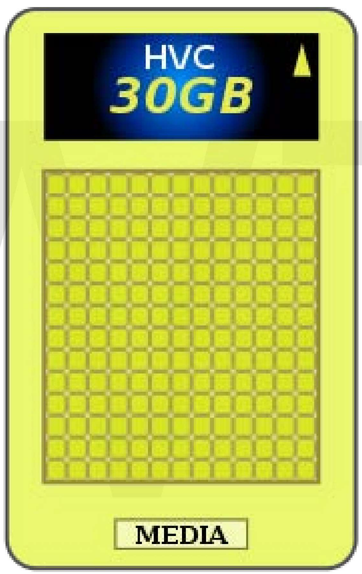
Electron holography is commonly used to study electric and magnetic fields in thin films, as magnetic and electric fields can shift the phase of the interfering wave passing through the sample.

The principle of electron holography can also be applied to interference lithography.

Chapter- 5

Holographic Memory

Holographic Versatile Card



Holographic Versatile Card

The **Holographic Versatile Card** (HVC) is a data storage format by Optware; the projected date for a Japanese launch had been the first half of 2007, pending finalization of the specification, however as of July 2010, nothing has yet surfaced. One of its main advantages compared with discs is the lack of moving parts when played. They claim it will hold 30GB of data, have a write speed 3 times faster than Blu-ray, and be approximately the size of a credit card. Optware claims that at release the media will cost about ¥100 (roughly $1) each, reader devices are set to cost about ¥200,000(roughly $1800) while reader/writer devices are to cost ¥1 000,000 (roughly $9000) each.

Holographic Versatile Disc

Holographic Versatile Disc

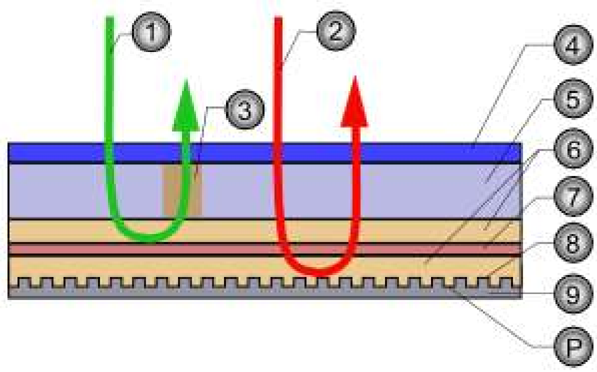
Picture of an HVD by Optware

Media type	Ultra-high density optical disc
Encoding	MPEG-2, MPEG-4 AVC (H.264), NGVC (H.265) and VC-1
Capacity	6 TB
Developed by	HSD Forum
Usage	Data storage, High-definition video, Quad HD & the possibility of Ultra HD

The **Holographic Versatile Disc** (**HVD**) is an optical disc technology developed between April 2004 and mid-2008 which can store the same amount of information as roughly twenty Blu-ray discs. It employs a technique known as collinear holography, whereby a green and red laser beam are collimated in a single beam. The green laser reads data encoded as laser interference fringes from a holographic layer near the top of the disc. A red laser is used as the reference beam to read servoinformation from a regular CD-style aluminum layer near the bottom. Servoinformation is used to monitor the position of the read head over the disc, similar to the head, track, and sector information on a conventional hard disk drive. On a CD or DVD this servoinformation is interspersed amongst the data.

A dichroic mirror layer between the holographic data and the servo data reflects the green laser while letting the red laser pass through. This prevents interference from refraction of the green laser off the servo data pits and is an advance over past holographic storage media, which either experienced too much interference, or lacked the servo data entirely, making them incompatible with current CD and DVD drive technology. These discs have the capacity to hold up to 6 terabytes (TB) of information. The HVD also has a transfer rate of 1 Gbit/s (125 MB/s). Sony, Philips, Lanix, TDK, Panasonic, and Optware all plan to release 1 TB capacity discs in 2019 while Maxell plan one for early 2020 with a capacity of 500 GB and transfer rate of 20 MB/s. GE also plans to release a form of HVD (The "General Electric holographic disc") sometime in the next few years with a storage capacity of 500GB. Sony insists that BluRay disc will have a minimum 10 years lifespan — and although HVD standards were approved and published on June 28, 2007, no company has released an HVD publicly as of December 2010.

Technology



Holographic Versatile Disc structure 1. Green writing/reading laser (532 nm) 2. Red positioning/addressing laser (650 nm) 3. Hologram (data)(shown here as brown) 4. Polycarbonate layer 5. Photopolymeric layer (data-containing layer) 6. Distance layers 7. Dichroic layer (reflecting green light) 8. Aluminum reflective layer (reflecting red light) 9. Transparent base P. Pit pattern

Current optical storage saves one bit per pulse, and the HVD alliance hopes to improve this efficiency with capabilities of around 60,000 bits per pulse in an inverted, truncated cone shape that has a 200 micrometer diameter at the bottom and a 500 micrometer diameter at the top. High densities are possible by moving these closer on the tracks: 100 GB at 18 micrometers separation, 200 GB at 13 micrometers, 500 GB at 8 micrometers, and most demonstrated of 5 TB for 3 micrometers on a 10 cm disc.

The system uses a green laser, with an output power of 1 watt which is quite high power for a consumer device laser. So a bigger challenge of the project for widespread consumer markets is to either improve the sensitivity of the polymer used, or develop and commoditize a laser capable of higher power output and suitable for a consumer unit.

Competing technologies

HVD is not the only technology in high-capacity, optical storage media. InPhase Technologies were developing a rival holographic format called Tapestry Media, which they claim will eventually store 1.6 TB with a data transfer rate of 120 MB/s, and several companies are developing TB-level discs based on 3D optical data storage technology. Such large optical storage capacities compete favorably with the Blu-ray Disc format. However, holographic drives are projected to initially cost around US$15,000, and a single disc around US$120–180, although prices are expected to fall steadily.

Holography System Development Forum

The Holography System Development Forum (HSD Forum; formerly the HVD Alliance and the HVD FORUM) is a coalition of corporations purposed to provide an industry forum for testing and technical discussion of all aspects of HVD design and manufacturing.

As of August 2009, the HSD Forum comprised these corporations:

- Hoplon Infotainment
- Alps Electric Corporation, Ltd.
- CMC Magnetics Corporation
- Hitachi
- Mitsubishi
- Apple Inc.
- Dainippon Ink and Chemicals, Inc. (DIC)
- EMTEC International (subsidiary of the MPO Group)
- Fuji Photo Film Company, Ltd.
- Konica Minolta Holdings, Inc.
- Lanix
- LiteOn Technology Corporation
- Moser Baer, (India)
- Mexican Digital Media Storage Organization
- Mitsubishi Kagaku Media Company, Ltd. (MKM)
- Nippon Kayaku Co., Ltd.
- Nippon Paint Company, Ltd.
- Optware Corporation
- Pulstec Industrial Company, Ltd.
- Shibaura Mechatronics Corporation
- Software Architects, Inc. (?)
- Suruga Seiki Company, Ltd.
- Targray Technology International, Inc.
- Teijin Chemicals, Ltd.
- Toagosei Company, Ltd.
- Tokiwa Optical Corporation

Standards

On December 9, 2004 at its 88th General Assembly, the standards body Ecma International created Technical Committee 44, dedicated to standardizing HVD formats based on Optware's technology. On June 11, 2007, TC44 published the first two HVD standards: ECMA-377, defining a 200 GB HVD "recordable cartridge" and ECMA-378, defining a 100 GB HVD-ROM disc. Its next stated goals are 30 GB HVD cards and submission of these standards to the International Organization for Standardization for ISO approval.

Holographic Associative Memory

Holographic Associative Memory is part of the family of analog, correlation-based, associative, stimulus-response memories, where information is mapped onto the phase orientation of complex numbers operating. It can be considered as a complex valued artificial neural network. The holographic associative memory exhibits some remarkable characteristics. Holographs have been shown to be effective for associative memory tasks, generalization, and pattern recognition with changeable attention. Ability of dynamic search localization is central to natural memory. For example, in visual perception, humans always tend to focus on some specific objects in a pattern. Humans can effortlessly change the focus from object to object without requiring relearning. It provides a computational model which can mimic this ability by creating representation for focus. At the heart of this new memory lies a novel bi-modal representation of pattern and a hologram-like complex spherical weight state-space. Besides the usual advantages of associative computing, this technique also has excellent potential for fast optical realization because the underlying hyper-spherical computations can be naturally implemented on optical computations.

InPhase Technologies

InPhase Technologies is a technology company developing holographic storage devices and media. InPhase was spun out from Bell Labs in 2000. Their technology eventually promises terabyte storage. In May 2008 the company was due to release their first reader, tapestry 300r, offering a storage capacity of 300 GB, with transfer rates of 20 MB/s in read write mode. However, the product was not released by this target date, marking the third time the company failed to release the reader on-time after previously setting release dates of late 2006, and then February 2007. As a result of these delays, InPhase was forced to cut a number of its workforce; currently there is no release date for the drive visible.

InPhase Technologies currently holds the record for "highest commercial data storage" by achieving 515 Gbit per square inch. of media. Most recently the company broke the 1 terabyte benchmark.

In February 2008, InPhase Technologies was granted a joint patent with video game company Nintendo for a flexure-based scanner for angle-based multiplexing in a holographic storage system.

On March 18, 2010, Signal Lake acquired a majority stake in the remains of Longmont based InPhase.

InPhase Technologies Group Inc.

InPhase shares its company name with a chiropractic practice management software company located in Rome, Georgia.

Chapter- 6

Holonomic Brain Theory and Computer-Generated Holography

Holonomic Brain Theory

The **holonomic brain theory**, originated by psychologist Karl Pribram and initially developed in collaboration with physicist David Bohm, is a model for human cognition that is drastically different from conventionally accepted ideas: Pribram and Bohm posit a model of cognitive function as being guided by a matrix of neurological wave interference patterns situated temporally between holographic Gestalt perception and discrete, affective, quantum vectors derived from reward anticipation potentials.

Pribram was originally struck by the similarity of the hologram idea and Bohm's idea of the implicate order in physics, and contacted him for collaboration. In particular, the fact that information about an image point is distributed throughout the hologram, such that each piece of the hologram contains some information about the entire image, seemed suggestive to Pribram about how the brain could encode memories. Pribram was encouraged in this line of speculation by the fact that DeValois and DeValois had found that "the spatial frequency encoding displayed by cells of the visual cortex was best described as a Fourier transform of the input pattern." This holographic idea led to the coining of the term "holonomic" to describe the idea in wider contexts than just holograms.

Lens-defined model of brain function

In this model, each sense functions as a lens, refocusing wave patterns either by perceiving a specific pattern or context as swirls, or by discerning discrete grains or quantum units. David Bohm has said that if you take the lenses away, what you are left with is a hologram.

According to Pribram and Bohm, "future orientation" is the essence of cognitive function, which they have attempted to define through use of the Fourier theorem and quantum mechanical formulae. According to Pribram, the tuning of wave frequency in cells of the primary visual cortex plays a role in visual imaging, while such tuning in the auditory system has been well established for decades. Pribram and colleagues also assert that similar tuning occurs in the somatosensory cortex.

Pribram distinguishes between propagative nerve impulses on the one hand, and slow potentials (hyperpolarizations, steep polarizations) that are essentially static. At this temporal interface, he indicates, the wave interferences form holographic patterns.

Pribram has written, "What the data suggest is that there exists in the cortex, a multidimensional holographic-like process serving as an attractor or set point toward which muscular contractions operate to achieve a specified environmental result. The specification has to be based on prior experience (of the species or the individual) and stored in holographic-like form. Activation of the store involves patterns of muscular contractions (guided by basal ganglia, cerebellar, brain stem and spinal cord) whose sequential operations need only to satisfy the 'target' encoded in the image of achievement much as the patterns of sequential operations of heating and cooling must meet the setpoint of the thermostat."

Quantum dynamics of free will

According to this theory, waveforms, within the matrix of a distributed system, allow fluctuations taking place to create new patterns, according to Pribram, and the resulting dynamic potential can then organize new foci of activity oriented to the precipitation of strategic planning and exercise of free will.

In a 1998 interview, Pribram addressed the understanding of cognitive potential, stating that, "(I)f you get into your potential mode, then new things can happen. But usually free will is conceived in terms of how many constraints are operating, and we have in statistics a notion of degrees of freedom. I think our will essentially is constrained, more or less. We have so many degrees of freedom, and the more degrees of freedom we have, the more we feel free, and we have freedom of choice."

These so-called "quantum minds" are still debated among scientists and philosophers, and there are actually a number of different theories—not one—that have been suggested. Notable proponents of various quantum mind theories are philosopher David Chalmers and mathematical physicist Roger Penrose. Cosmologist Max Tegmark is a notable opponent of the various quantum mind theories. Tegmark wrote the well-known paper, "Problem with Quantum Mind Theory," which demonstrates certain problems with Chalmers' and Penrose's ideas on the subject.

Computer-generated holography

Computer Generated Holography (CGH) is the method of digitally generating holographic interference patterns. A holographic image can be generated e.g. by digitally computing a holographic interference pattern and printing it onto a mask or film for subsequent illumination by suitable coherent light source.
Alternatively, the holographic image can be brought to life by a holographic 3D display (a display which operates on the basis of interference of coherent light), bypassing the need of having to fabricate a "hardcopy" of the holographic interference pattern each time. Consequently, in recent times the term "computer generated holography" is increasingly being used to denote the whole process chain of synthetically preparing holographic light wavefronts suitable for observation.

Computer generated holograms have the advantage that the objects which one wants to show do not have to possess any physical reality at all (completely synthetic hologram generation). On the other hand, if holographic data of existing objects is generated optically, but digitally recorded and processed, and brought to display subsequently, this is termed CGH as well. Ultimately, computer generated holography might serve all the roles of current computer generated imagery: holographic computer displays for a wide range of applications from CAD to gaming, holographic video and TV programs, automotive and communication applications (cell phone displays) and many more.

Overview

Holography is a technique originally invented by Hungarian physicist Dennis Gabor (1900-1979) to improve the resolving power on electron microscopes. An object is illuminated with a coherent (usually monochromatic) light beam; the scattered light is brought to interference with a reference beam of the same source, recording the interference pattern. CGH as defined in the introduction has broadly three tasks:

1. **Computation** of the virtual scattered wavefront
2. **Encoding** the wavefront data, preparing it for display
3. **Reconstruction**: **Modulating** the interference pattern onto a coherent light beam by technological means, to transport it to the user observing the hologram.

Note that it is not always justified to make a strict distinction between these steps; however it helps the discussion to structure it in this way.

Wavefront computation

Computer generated holograms offer important advantages over the optical holograms since there is no need for a real object. Because of this a breakthrough in three-dimensional display was expected when the first algorithms were reported at 1966.

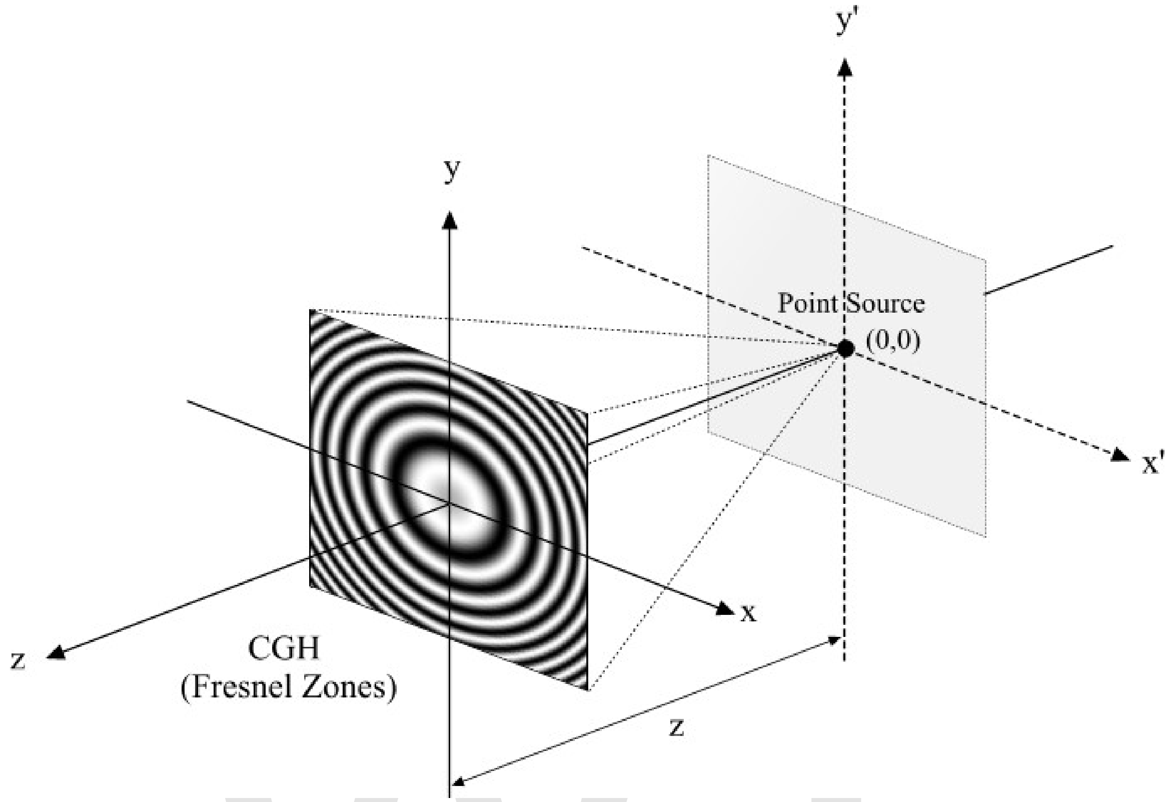
Unfortunately, the researchers have very soon realized that there a noticeable lower and upper bounds in terms of computational speed and image quality and fidelity respectively. Wavefront calculations are computationally very intensive; even with modern mathematical techniques and high-end computing equipment, real-time computation is tricky. There are many different methods for calculating the interference pattern for a CGH. In the next 25 years a lot of methods for CGHs have been proposed in the fields of holographic information and computational reduction as well as in computational and quantization techniques. In the field of computational techniques the reported algorithms can be categorized in two main concepts.

Fourier transform method

In the first one the Fourier transformation is used to simulate the propagation of each plane of depth of the object to the hologram plane. The Fourier transformation concept was first introduced by Brown and Lohmann with the detour phase method leading to cell oriented holograms. A coding technique suggested by Burch replaced the cell oriented holograms by point holograms and made this kind of computer generated holograms more attractive. In a Fourier Transform hologram the reconstruction of the image occurs in the far field. This is usually achieved by using the Fourier transforming properties of a positive lens for reconstruction. So there are two steps in this process: computing the light field in the far observer plane, and then Fourier transforming this field back to the lens plane. These holograms are called Fourier Based Holograms. First CGHs based on the Fourier transform could reconstruct only 2D images. Brown and Lohmann introduced a technique to calculate computer generated holograms of 3D objects. Calculation of the light propagation from three-dimensional objects is performed according to the usual parabolic approximation to the Fresnel-Kirchhoff diffraction integral. The wavefront to be reconstructed by the hologram is, therefore, the superposition of the Fourier transforms of each object plane in depth, modified by a quadratic phase factor.

Point Source Holograms

The second computational strategy is based on the point source concept, where the object is broken down in self-luminous points. An elementary hologram is calculated for every point source and the final hologram is synthesized by superimposing all the elementary holograms. This concept has been first reported by Waters whose major assumption originated with Rogers who recognized that a Fresnel zone plate could be considered a special case of the hologram proposed by Gabor. But, as far as most of the object points were non-zero the computational complexity of the point-source concept was much higher than in the Fourier



transformation concept. Some researchers tried to overcome this drawback by predefining and storing all the possible elementary holograms using on top special data storage techniques because of the huge capacity that is needed in this case, others by using special hardware. In the point-source concept the major problem that has to be circumvented is the competition among data storage capacity and computational speed. In particular, algorithms that rise the computational speed need usually very high data storage capabilities while on the other side algorithms that lower the need of data storage capacity lead to high computational complexity though some optimizations could be achieved. Another concept which leads to Point Source CGHs is the **Ray tracing method**. Ray tracing is perhaps the simplest method of computer generated holography to visualize. Essentially, the path length difference between the distance a virtual "reference beam" and a virtual "object beam" have to travel is calculated; this will give the relative phase of the scattered object beam.

Over the last three decades both concepts have made a remarkable progress improving computational speed and image quality. However, some technical restraints like computational and storage capacity still burden digital holography making potential real-time applications with current standard computer hardware almost impossible.

Interference pattern encoding

Once it is known how the scattered wavefront of the object looks like or how it may be computed, it must be fixed on a spatial light modulator (SLM), abusing this term to include not only LCD displays or similar devices, but also films and masks. Basically, there are different types of SLMs available: Pure phase modulators (retarding the illuminating wave), pure amplitude modulators (blocking the illumination light), and SLMs which have the capability of combined phase/amplitude modulation.

In the case of pure phase or amplitude modulation, clearly quality losses are unavoidable. Early forms of pure amplitude holograms were simply printed in black and white, meaning that the amplitude had to be encoded with one bit of depth only. Similarly, the kinoform is a pure-phase encoding invented at IBM in the early days of CGH. Even if a fully complex phase/amplitude modulation would be ideal, a pure phase or pure amplitude solution is normally preferred because it is much easier to implement technologically.

Reconstruction

The third (technical) issue is beam modulation and actual wavefront reconstruction. Masks may be printed, resulting often in a grained pattern structure since most printers can make only dots (although very small ones). Films may be developed by laser exposure. Holographic displays are currently yet a challenge (as of 2008), although successful prototypes have been built. An ideal display for computer generated holograms would consist of pixels smaller than a wavelength of light with adjustable phase and brightness. Such displays have been called phased array optics. Further progress in nanotechnology is required to build them.

Chapter- 7

Holographic Screen and Reciprocity

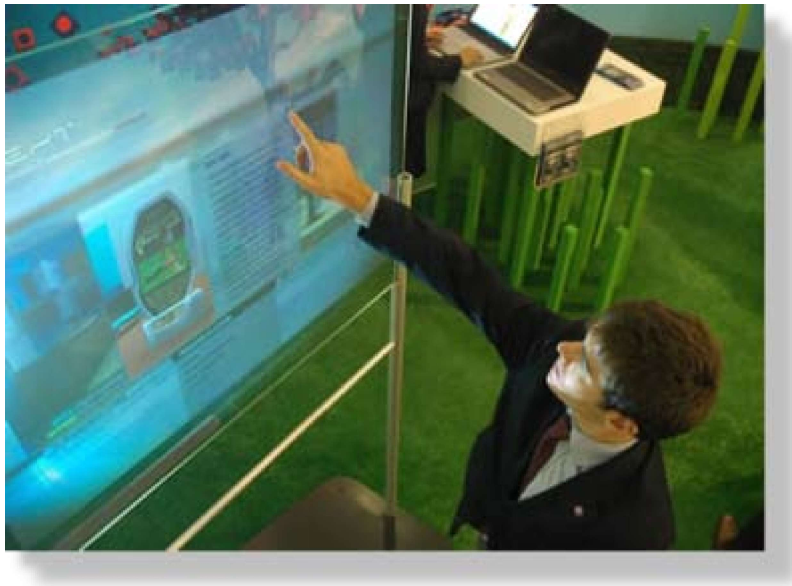
Holographic screen

A **holographic screen** is a display technology that uses coated glass media for the projection surface of a video projector. "Holographic" refers to the coating that bundles light using formed microlenses. The lens design and attributes match the holographic area. The lenses may have a very rough similarity with the fresnel lenses used in overhead projectors. The whole appearance often looks rather similar to a free-space display since the image carrier appears very transparent. The beam manipulation by the lenses might make the image appear not directly on the glass but with some offset. Still such a display is only 2D and not true 3D. At present it is unclear if such a technology can provide acceptable 3D images.

Working principle

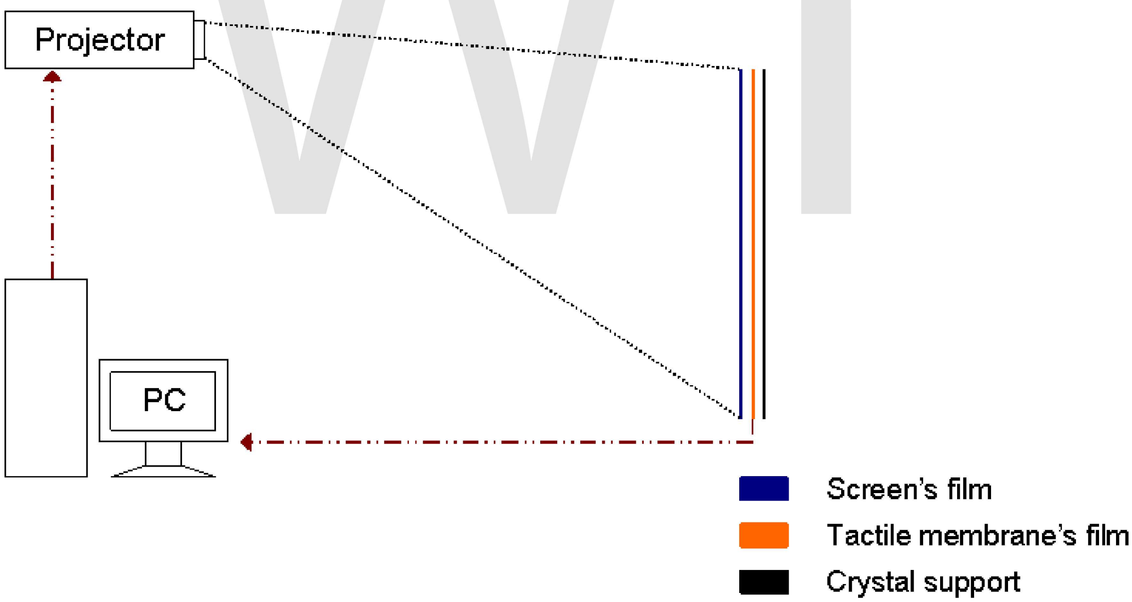
The display design can use either front or rear projection. One or more video projectors point to the glass plate. The beam widens towards the surface and then is bundled again by the lenses' arrangement on the glass. This forms a virtual point of origin so that the viewer is deceived into envisioning an imaginary object somewhere close to the glass as the image source. In rear projection the light passes through the glass. In front projection it is reflected. Rear projection is the common use case.

Interactive holographic screens



Interactive holographic screens add gesture support to holographic screens.

How does it work?



Scheme

The system used on holographic interactive screens is formed from three basic components:

- A projector
- A computer

- Two films

The computer sends the image to the projector. The projector generates light two beams which forming the image on the screen. Finally, the user touches the screen, a membrane film reacts to these movements, generates electrical impulses and sends them to the computer. The computer interprets the received impulses and modifies the projected image according to the information.

Projector

The projector generates the beams of light that will form the image on the screen's film adhered on the crystal support. It's placed behind the screen. It must be placed a certain angle above or below this to avoid the dazzle of the user. It must be trapezoidal projector which allows a certain angle of displacement without deforming the images.

Computer

The computer controls the system. It manages the images that it projects and the impulses from the tactile membrane that provide the interactivity.

Films

Film

The films are caps of plastic that stick to the crystal and that allow both visualization and interactivity. There are two types of films:

- Screen film: This film can be opaque or transparent. It is possible to work with different degrees of opacity that can vary between 90% and 98%, depending on the application (interior, exterior, natural lighting, artificial lighting...)

- Tactile membrane: This film enables interactivity. Capacitive projected technology catches user gestures and sends impulses to the computer.

Specifications

- The crystals where the images are projected can be a maximum 16 millimeters (0.6 in) wide.
- The projection films can vary from 40 inches (102 cm) and 100 inches (254 cm).
- The whole montage must be realized in the posterior part of the crystal to allow interactivity.

Uses

The most used applications are interactive shop windows. The holographic interactive screen is mounted on the shop window's so that passersby can interact with it.

Most initial uses of this technology are advertising-related.

Another type of holographic screens that is not interactive is also placed in shop windows. These have artificial vision software that adapts ads depending on the viewer's characteristics (age, sex...).

Reciprocity

In photography and holography, **reciprocity** refers to the inverse relationship between the intensity and duration of light that determines the reaction of light-sensitive material. Within a normal exposure range for film stock, for example, the **reciprocity law** states that the film response will be determined by the total exposure, defined as intensity × time. Therefore, the same response (for example, the optical density of the developed film) can result from reducing duration and increasing light intensity, and vice versa.

The reciprocal relationship is assumed in most sensitometry, for example when measuring a Hurter and Driffield curve (optical density versus logarithm of total exposure) for a photographic emulsion. Total exposure of the film or sensor, the product of focal-plane illuminance times exposure time, is measured in lux seconds.

History

The idea of reciprocity, once known as Bunsen–Roscoe reciprocity, originated from the work of Robert Bunsen and Henry Roscoe in 1862.

Deviations from the reciprocity law were reported by Captain William de Wiveleslie Abney in 1893, and extensively studied by Karl Schwarzschild in 1899. Schwarzschild's model was found wanting by Abney and by Englisch, and better models have been proposed in subsequent decades of the early twentieth century. In 1913, Kron formulated an equation to describe the effect in terms of curves of constant density, which J. Halm adopted and modified, leading to the "Kron–Halm catenary equation" or "Kron–Halm–Webb formula" to describe departures from reciprocity.

In chemical photography

In photography, *reciprocity* refers to the relationship whereby the total light energy – proportional to the total exposure, the product of the light intensity and exposure time, controlled by aperture and shutter speed, respectively – determines the effect of the light on the film. That is, an increase of brightness by a certain factor is exactly compensated by a decrease of exposure time by the same factor, and vice versa. In other words there is under normal circumstances a reciprocal proportion between aperture area and shutter speed for a given photographic result, with a wider aperture requiring a faster shutter speed for the same effect. For example, an EV of 10 may be achieved with an aperture (f-number) of f/2.8 and a shutter speed of 1/125 s. The same exposure is achieved by doubling the aperture area to f/2 and halving the exposure time to 1/250 s, or by halving the aperture area to f/4 and doubling the exposure time to 1/60 s; in each case the response of the film is expected to be the same.

Reciprocity failure

For most photographic materials, reciprocity is valid with good accuracy over a range of values of exposure duration, but becomes increasingly inaccurate as we depart from this range: **reciprocity failure**, **reciprocity law failure**, or **Schwarzschild effect**. As the light level decreases out of the reciprocity range, the increase in duration, and hence of total exposure, required to produce an equivalent response becomes higher than the formula states; for instance, at half of the light required for a normal exposure, the duration must be more than doubled for the same result. Multipliers used to correct for this effect are called *reciprocity factors* (see model below).

At very low light levels, film is less responsive. Light can be considered to be a stream of discrete photons, and a light-sensitive emulsion is composed of discrete light-sensitive grains, usually silver halide crystals. Each grain must absorb a certain number of photons in order for the light-driven reaction to occur and the latent image to form. In particular, if the surface of the silver halide crystal has a cluster of approximately four or more reduced silver atoms, resulting from absorption of a sufficient number of photons (usually a few dozen photons are required), it is rendered developable. At low light levels, *i.e.* few photons per unit time, photons impinge upon each grain relatively infrequently; if the four photons required arrive over a long enough interval, the partial change due to the first one or two is not stable enough to survive before enough photons arrive to make a permanent latent image center.

This breakdown in the usual tradeoff between aperture and shutter speed is known as reciprocity failure. Each different film type has a different response at low light levels. Some films are very susceptible to reciprocity failure, and others much less so. Some films that are very light sensitive at normal illumination levels and normal exposure times lose much of their sensitivity at low light levels, becoming effectively "slow" films for long exposures. Conversely some films that are "slow" under normal exposure duration retain their light sensitivity better at low light levels.

For example, for a given film, if a light meter indicates a required EV of 5 and the photographer sets the aperture to f/11, then ordinarily a 4 second exposure would be required; a reciprocity correction factor of 1.5 would require the exposure to be extended to 6 seconds for the same result. Reciprocity failure generally becomes significant at exposures of longer than about 1 sec for film, and above 30 sec for paper.

Reciprocity also breaks down at extremely high levels of illumination with very short exposures. This is concern for scientific and technical photography, but rarely to general photographers, as exposures significantly shorter than a millisecond are only required for subjects such as explosions and particle physics experiments, or when taking high-speed motion pictures with very high shutter speeds (1/10,000 sec or faster).

Schwarzschild law

In response to astronomical observations of low intensity reciprocity failure, Karl Schwarzschild wrote (circa 1900):

> "In determinations of stellar brightness by the photographic method I have recently been able to confirm once more the existence of such deviations, and to follow them up in a quantative way, and to express them in the following rule, which should replace the law of reciprocity: Sources of light of different intensity *I* cause the same degree of blackening under different exposures *t* if the products $I \times t^{0.86}$ are equal."

Unfortunately, Schwarzschild's empirically determined *0.86* coefficient turned out to be of limited usefulness. A modern formulation of **Schwarzschild's law** is given as

$$E = It^p$$

where E is a measure of the "effect of the exposure" that leads to changes in the opacity of the photosensitive material (in the same degree that an equal value of exposure $H = It$ does in the reciprocity region), I is illuminance, t is exposure duration and p is the *Schwarzschild coefficient*.

However, a constant value for p remains elusive, and has not replaced the need for more realistic models or empirical sensitometric data in critical applications. When reciprocity holds, Schwarzschild's law uses $p = 1.0$.

Since the Schwarzschild's law formula gives unreasonable values for times in the region where reciprocity holds, a modified formula has been found that fits better across a wider range of exposure times. The modification is in terms of a factor the multiplies the ISO film speed:

$$\text{Relative film speed} = (t+1)^{(p-1)}$$

where the $t + 1$ term implies a breakpoint near 1 second separating the region where reciprocity holds from the region where it fails.

Simple model for *t* > 1 second

Some models of microscope use automatic electronic models for reciprocity failure compensation, generally of a form for correct time, T_c, expressible as a power law of metered time, T_m, that is, $T_c=(T_m)^p$, for times in seconds. Typical values of p are 1.25 to 1.45, but some are low as 1.1 and high as 1.8.

The Kron–Halm catenary equation

Kron's equation as modified by Halm states that the response of the film is a function of It/ψ, with the factor defined by an catenary (hyperbolic cosine) equation accounting for reciprocity failure at both very high and very low intensities:

$$\psi = \frac{1}{2}[(I/I_0)^a + (I/I_0)^{-a}]$$

where I_0 is the photographic material's optimum intensity level and a is a constant that characterizes the material's reciprocity failure.

Quantum reciprocity-failure model

Modern models of reciprocity failure incorporate an exponential function, as opposed to power law, dependence on time or intensity at long exposure times or low intensities, based on the distribution of *interquantic times* (times between photon absorptions in a grain) and the temperature-dependent *lifetimes* of the intermediate states of the partially-exposed grains.

Baines and Bomback explain the "low intensity inefficiency" this way:

> “ Electrons are released at a very low rate. They are trapped and neutralised and must remain as isolated silver atoms for much longer than in normal latent image formation. It has already been observed that such extreme sub-latent image is unstable, and it is postulated that ineffiency is caused by many isolated atoms of silver losing their acquired electrons during the period of ”

instability.

Astrophotography

Reciprocity failure is an important effect in the field of film-based astrophotography. Deep-sky objects such as galaxies and nebulae are often so faint that they are not visible to the un-aided eye. To make matters worse, many objects' spectra do not line up with the film emulsion's sensitivity curves. Many of these targets are small and require long focal lengths, which can push the focal ratio far above f/5. Combined, these parameters make these targets extremely difficult to capture with film; exposures from 30 minutes to well over an hour are typical. As a typical example, capturing an image of the Andromeda Galaxy at f/4 will take about 30 minutes; to get the same density at f/8 would require an exposure of about 200 minutes.

When a telescope is tracking an object, every minute is difficult; therefore, reciprocity failure is one of the biggest motivations for astronomers to switch to digital imaging. Electronic image sensors have their own limitation at long exposure time and low illuminance levels, not usually referred to as reciprocity failure, namely noise from dark current, but this effect can be controlled by cooling the sensor.

Holography

A similar problem exists in holography. The total energy required when exposing holographic film using a continuous wave laser (i.e. for several seconds) is significantly less than the total energy required when exposing holographic film using a pulsed laser (i.e. around 20–40 nanoseconds) due to a reciprocity failure. It can also be caused by very long or very short exposures with a continuous wave laser. To try to offset the reduced brightness of the film due to reciprocity failure, a method called latensification can be used. This is usually done directly after the holographic exposure and using an incoherent light source (such as a 25-40 W light bulb). Exposing the holographic film to the light for a few seconds can increase the brightness of the hologram by an order of magnitude.

Chapter- 8

Sonic Holography and Volume Hologram

Sonic holography

Sonic Holography is a proprietary audio filter design developed by Bob Carver that was used extensively in several preamplifier and receiver units, as well as in the standalone model C-9, built by Carver Corporation in the 1980s and 1990s.

The goal of sonic holography is to remove distortions in pitch caused by the doppler effect while recording and playing back audio on a sound system. While an audio source is recorded by a microphone, the membrane that picks up sound vibrations moves towards and away from the source. This results in a doppler shift that is preserved in the recording. When that recording is played through a speaker, the cone vibrates back and forth in order to move air particles and create sound. This introduces a second doppler shift, especially when the same cone is producing multiple frequencies at the same time. Both instances of doppler distortion degrade the overall quality of the output. Sonic holography attempts to remove these distortions using a proprietary filter designed by Bob Carver.

Dissenting Opinion: Sonic Holography is Bob Carver's handle for interaural crosstalk cancellation, NOT distortions caused by the doppler effect.

Controversy

Agreement on dissenting opinion

Bob Carver's literature and design theory never mention the Doppler Effect. His early technology focused on reducing the crosstalk to provide a very realistic sound stage with only the two stereo speakers. Placement of the speakers, reduction in early reflections and precise listener location made the acceptance by the consumer less than enthusiastic. It must be said that when set up correctly the effect was unreal. A complete 180-degree sound stage could be perceived by the listener. It was positively hypnotic and induced a feeling of disbelief.

Audio purists argue that in order to preserve fidelity, the audio signal should be captured at the highest quality possible and then should not be modified. Some listeners feel that

Sonic Holography introduces artifacts into the sound recording while attempting to remove others.

The Original Description

The above article misrepresents what Bob Carver's invention of Sonic Holography is and does. I have taken the following information about Sonic Holography from the user manual of the device where Sonic Holography was first introduced: **Carver Model C4000 High Fidelity Control Console ©1981 by Carver Corporation.** In that this preamplifier was the first to incorporate Sonic Holography, it contains an extensive explanation of the underlying theory of its operation.

SONIC HOLOGRAM Stereo Image Processor

"Sonic Holography" is a method of processing stereo signals so as to correct a basic imaging flaw which is inherent in two-channel stereophonic recording and reproduction via loudspeakers. What that flaw is and why it can't be corrected by any conventional recording technique are discussed later in **"Stereo Recording and Playback"**.

Briefly, the problem is that in stereo listening, both ears hear the outputs of both loudspeakers. When a sonic event such as a musical transient is reproduced by the Left-channel loudspeaker, the sound travels in a straight line from the speaker to your left ear. A tiny fraction of a second later the same Left-loudspeaker sound arrives at your right ear, somewhat filtered by the obstruction of your head. If the same sonic event was recorded in both stereo channels, as normally is the case, then some version of it will be reproduced in the Right-channel speaker, whose sound will arrive at your right ear and then, a tiny fraction of a second later, at your left ear. Thus the single original sonic event is represented by a total of **four** sound arrivals at your two ears.

In real life a single sonic event can never cause more than two sonic arrivals: one at your left ear and one at your right ear. (Which ear gets the sound first depends on which direction you are facing, relative to where the sound is coming from. If you are facing the sound, it will arrive at both ears simultaneously.)

The goal of the Carver Sonic Hologram Generator is to eliminate the "extra" two sonic arrivals that occur in stereophonic playback but do not occur in real life. With these eliminated, the ear/brain system of the listener will receive unambiguous timing and phase information about the original sounds as they struck the recording microphones. Without extra sonic arrivals to confuse it, the ear/brain system will be able to perceive the true location of each sound source in the stereo recording — not only from left to right but also from near to far.

This is accomplished by canceling the unwanted second arrival of the sound from each speaker to the opposite side ear, so that each ear is free to concentrate its attention on the signal from the speaker on the same side; i.e., the left ear will hear mainly the Left speaker, and the right ear will hear mainly the Right speaker, without the confusing acoustic crosstalk which normally occurs in stereo playback.

How it works. The circuit produces electronic crosstalk signals from each stereo channel into the opposite-side speaker. These are virtually identical to the unwanted acoustic crosstalk second-arrival signals which flatten the image in stereo. They have essentially the same delays as the second-arrival signals, and about the same filtering as that caused by the blockage of your head, but they are inverted in phase. Consequently, when these mirror-image crosstalk signals are reproduced by your speakers they cancel the acoustic crosstalk signals arriving at each ear from the opposite speaker.

Stereo Recording and Playback

If the sound is recorded and later played back in stereo via loudspeakers, the result will depend on the microphone technique employed. Consider the simplest and most common: the sound is recorded via a single close-up microphone whose signal is "panpotted," i.e., split and recorded in both stereo channels but slightly stronger in the left channel in order to place its image slightly to the left of center. In playback the sound emerges simultaneously from both speakers (a little louder in the left).

Assume that you are sitting equally distant from the two speakers, facing the midpoint between them. The sound from the left speaker arrives at your left ear, and at the same time the sound from the right speaker arrives at your right ear. A fraction of a millisecond later the sound from the left speaker, after filtering by the acoustic shadow of your head, arrives at your right ear; and similarly the sound from the right speaker arrives at your left ear.

In the "live" listening experience the single sonic event produces two arrivals at the ear. The delay and frequency spectrum differences between the two ears are the primary cues which the brain uses to determine the direction of the sound source. In the "panpotted" stereo recording and playback, the sonic event has produced a total of four arrivals at the ears, the first two being simultaneous and identical in frequency spectrum — a very different set of cues.

In an effort at greater realism, some recording engineers attempt to record musical performances with a "coincident pair" of crossed cardioid or figure-8 microphones. The sound from the instrument, regardless of where it is located on the stage, arrives simultaneously at the two mikes and is recorded in both channels, with a difference in intensity which is proportional to the source's angular displacement away from stage center. Thus in playback the sound emerges simultaneously from both loudspeakers, with some difference in strength; but just as with panpotting, the original sonic event generates a total of four sound arrivals at the ears.

The other common technique for recording large ensembles such as symphony orchestras and choruses is to hang two microphones in front of the stage, separated by about eight feet. Now, if the instrument is located several feet left of stage center, its sound will reach the left microphone first and will get to the right microphone after an extra air-path delay of, say, three milliseconds. As with the previous examples the sound of each instrument is present in both channels of the recording, but in theis case with a time-delay as well as an intensity difference between the two channels.

In playback the sound emerges for the left speaker, is heard by your left ear, and arrives at your right ear with some head-shadow loss after a small fraction of a millisecond. Meanwhile, three milliseconds after its appearance in the left speaker, the sound emerges from the right speaker and arrives successively at the right and left ears in turn. Not only do four sonic arrivals at the ears arise from the single sonic event — this time they are spread out be several milliseconds in time because of the spacing of the recording microphones. (In life a single event cannot generatearrivals spaced more than one millisecond apart, since no one's ears are spaced more than a foot apart.)

There are additional stereo miking techniques in common use, but all share the characteristic that every sound is present to some degree in both channels. Therefore every sonic event always produces four sonic arrivals at the ears in stereo playback — instead of two which in life provide the brain's primary cue to localizing the direction of sound. Of course this problem is avoided in a "ping-pong" recording, in which sound emerges only from the left or only from the right; but that's not stereo and cannot present a panoramic image spanning the space between the speakers.

One successful approach to lifelike sound reproduction is binaural recording, using microphones buried in a dummy head so that the recorded signals already contain the inter-aural delays and head-shadow losses which the listener would experience. The recording is played through headphones, so that each ear hears only what the same-side microphone in the dummy head picked up. This method is not without technical flaws, but its most important limitation is economic; most listeners don't like to be confined to headphone listening, so binaural recordings have very limited sales potential. As a practical matter most recordings must be engineered for loudspeaker playback.

Therefore, we need a direct solution to the problem of acoustic crosstalk in the listening environment. This is the goal of the Carver Sonic Hologram Generator.

SONIC HOLOGRAPHY: Canceling Acoustic Crosstalk

As noted earlier, the essence of the problem is that both ears hear the sounds from both loudspeakers. The sound from each speaker reaches the same-side ear directly and then, after a brief delay and loss due to acoustic blockage of the listener's head, reaches the opposite-side ear. Conceptually, the object of sonic holography is simply to cancel out that delayed, attenuated signal from reaching the opposite-side ear, so that each ear will be exposed mainly to just the speaker on the same side.

In principle it is quite straightforward. We know that the signal form the left-channel speaker arrives first at the left ear, then arrives in a slightly weaker form at the right ear after an added delay of about 0.2 milliseconds with its highs rolled off. All we have to do is to feed the right speaker a sample of the left-channel sound that is delayed 0.2 ms and rolled off in highs. This signal from the right speaker will get to the right ear simultaneously with the unwanted acoustic crosstalk signal from the left speaker. So if we phase-invert our specially-delayed right-speaker sample of the left channel signal, this electrical crosstalk will cancel the acoustic-crosstalk as the two signals arrive at the right ear. A complementary process is used to cancel the acoustic crosstalk from the right speaker into the left ear.

The actual operation of the Carver Sonic Holography Generator circuit is rather more complex than this, but that is the basic operating principle.

Why is this process called sonic holography? An optical hologram is a photograph made with a laser whose coherent beam of light is split into two beams and used to illuminate an object; the two beams are recombined, forming alternating rings of constructive and destructive interference. When the photograph is developed and another laser is used to project it, a three-dimensional image of the object is projected into space.

By analogy, a sonic hologram generator takes the beam of sound produced by each loudspeaker and splits it so that a related beam of sound is produced by the opposite speaker (after delay and filtering) in such a way that the acoustic interference of the sounds occurs in the air near each ear, revealing the true three-dimensional sound image that was hidden in the stereo recording. Recall that "stereo," in the original Greek, means "solid" or three-dimensional, not just wide. Ideally stereo is intended not only to paint a sonic image onto the wall between the loudspeakers but to yield realistic perception of depth as well.

Volume hologram

Volume holograms are holograms where the thickness of the recording material is much larger than the light wavelength used for recording. In this case diffraction of light from the hologram is possible only as Bragg diffraction, i.e., the light has to have the right wavelength (color) and the wave must have the right shape (beam direction, wavefront profile). Volume holograms are also called "thick holograms" or "Bragg holograms".

Theory

Volume holograms were first treated by H. Kogelnik in 1969 by the so-called "coupled-wave theory". For volume *phase* holograms it is possible to diffract 100% of the incoming reference light into the signal wave, i.e., full diffraction of light can be achieved. Volume *absorption* holograms show much lower efficiencies. H. Kogelnik provides analytical solutions for transmission as well as for reflection conditions. A good text-book description of the theory of volume holograms can be found in a book from J. Goodman.

Bragg selectivity

In the case of a simple Bragg reflector the wavelength selectivity $\Delta\lambda$ can be roughly estimated by $\Delta\lambda/\lambda \approx \Lambda/L$, where λ is the vacuum wavelength of the reading light, Λ is the period length of the grating and L is the thickness of the grating. The assumption is just that the grating is not too strong, i.e., that the full length of the grating is used for light diffraction. Considering that because of the Bragg condition the simple relation $\Lambda = \lambda / (2n)$ holds, where n is the refractive index of the material at this wavelength, one sees that for typical values ($\lambda = 500 \text{ nm}, \ L = 1 \text{ cm}, \ n = 1.5$) one gets $\Delta\lambda/\lambda \approx 10^{-5}$ showing the extraordinary wavelength selectivity of such volume holograms.

In the case of a simple grating in the transmission geometry the angular selectivity $\Delta\Theta$ can be estimated as well: $\Delta\Theta \approx \Lambda/d$, where d is the thickness of the holographic grating. Here Λ is given by $\Lambda = (\lambda / 2\sin\Theta)$. Using again typical numbers ($\lambda = 500 \text{ nm}, \ d = 1 \text{ cm}, \ \Theta = 45^\circ$) one ends up with $\Delta\Theta \approx 4 \times 10^{-5} \text{ rad} = 0.002^\circ$ showing the impressive angular selectivity of volume holograms.

Applications of volume holograms

The Bragg selectivity makes volume holograms very important. Prominent examples are:

- Distributed feedback lasers (DFB lasers) as well as distributed Bragg reflector lasers (DBR lasers) where the wavelength selectivity of volume holograms is used to narrow the spectral emission of semiconductor lasers.
- Holographic memory devices for holographic data storage where the Bragg selectivity is used to multiplex several holograms in one piece of holographic recording material using effectively the third dimension of the storage material.
- Fiber Bragg gratings that employ volume holographic gratings encrypted into an optical fiber.
  Wavelength filters that are used as an external feedback in particular for semiconductor lasers. Although the idea is similar to that of DBR lasers, these filters are not integrated onto the chip. With the help of such filters also high-power laser diodes become narrow-band and less temperature sensitive.

Chapter- 9

Australian Holographics

Australian Holographics was started with the specific objective to produce high quality large format holograms. After two years of research and development the company began commercial operations in 1991.

Situated on 80 acres (320,000 m^2) of rural farm land 25 miles (40 km) from Adelaide, the lab's facilities included a 5 x 6 metre vibration isolation table in a studio with air-lock loading doors, large enough to drive a car onto the main table. The main CW (continuous wave) laser was a 6W argon laser built by Coherent Scientific. The company also used a 3 joule ruby pulse laser, built in collaboration with Professor Jesper Munch of the School of Chemistry and Physics at Adelaide University.

The company mainly specialized in the production of the large format white-light-viewable Rainbow hologram, a type of holography originally invented in 1968 by Dr. Stephen Benton of MIT. IN fact, while all Rainbow Holograms are 'white-light-viewable' the most commonly known application of the technique has been applied to reflectve substrates like PVC (Polyvinyl Chloride) and PET (Poly Ethylene Terephthalate) and used widely on credit cards and as anti-counterfeiting applications on labeling of products. Australian Holographics applied the principle for transmission rather than reflective viewing conditions. In 1992, Australian Holographics produced a 2 x 1 metre rainbow transmission hologram of a Mitsubishi Station Wagon car, which was shown at Holographics International '92 conference in London.

Creating a Large Format Studio

The AH project necessitated building a large climate controlled studio incorporating a 6 x 5 metre optical table weighing around 25 tons. The system had to allow for both the creation of large-depth scenes for mastering, in addition to affording the space required for the effective production of ultra-large format rainbow transmission and reflection hologram copies. A heavy sand-filled cavity steel construction was used for the table. The suspension system was constructed around nine Firestone air bags connected to a standard pneumatic set-up with needle-valves, ballast tank and compressor. Overhead towers were designed to carry large transfer mirrors at heights of over three metres above the table. These towers were constructed from hollow steel tubes filled with sand. Over the years, lifting systems for the large glass filmholders evolved from hand operated, to mechanical and finally to pneumatic.

Imaging Techniques in Large Format Continuous Wave Holography

The requirement for stability in the CW (continuous wave) mastering process, has a surprisingly beneficial aspect, in that it allows for the utilization of unstable curtained areas to effectively render invisible unwanted elements in the field of vision. This trick is still unique to CW and is sorely missed during Pulse Holography mastering, where the problem is that often too many things are visible and there are limited methods available to conceal them. Thus if a large object is required to apparently float unsupported in space, CW mastering, rather than Pulsed, provides the means to easily achieve this illusion. Many important elements involved in producing high quality large format holograms rest not so much with the traditional concerns of holography but rather with aesthetic concerns that relate to table layout, and lighting techniques that endeavour to feature the subject without visual distractions and to control glare and reflections that lead to non-linear noise.

The specifications of the vertical film alignment in the holographic camera

During the holographic mastering process for large format Rainbow Transmission Holograms the strip of holographic film that becomes the H1 hologram master must be positioned in front of the subject (3D model) in such a way that it is bathed in diffused laser light, but importantly, must be held rigidly and firmly flat against a sheet of glass. Typically, elaborate hydraulic or vacuum systems have been employed to compress holographic film during the exposure process. However this function was achieved at Australian Holographics by the construction of what was referred to as 'the camera'. In fact the camera was a very long and narrow glass box, approximately 2.2 metres long, about 12 cm high and about 6 cm deep. Inside this 'camera' was a loose piece of glass slightly shorter than the length of the camera, but around the same height.

The surprising utility of: Johnson's Baby Oil

The long strip of holographic film was placed between the loose glass sheet and the front of the camera, and the entire camera box was then almost filled with Johnson's Baby Oil. This unusual element to the high tech array of equipment and processes came about after the exhaustive testing of the refractive index of countless varieties of commercially available oils, and to the surprise of the holographers concerned, none could surpass the efficacy of this product. The function of the oil inside the camera was to act as an agent to cause the camera to flatten the film between the two glass surfaces. As the oil slowly seeped out between the film's surface and the two glass sheets the natural viscosity of the oil maintained an ultra-thin but cohesive layer that had the effect of gradually pulling the two glass sheets together with a level of force sufficient to flatten the film to within the tolerance level that allowed a consistent interference pattern to be recorded on the H1 master.

History

Australian Holographics Pty Ltd. was incorporated in Adelaide, South Australia in 1989 by Dr. David Brotherton Ratcliffe. Dr. Ratcliffe was at the time a Research Fellow in Physics in the School of Physical Sciences, at Flinders University. The senior holographers working with Dr. Ratcliffe were initially Mr. Geoffrey Fox, and subsequently Mark Trinne.

In 1992, David Ratcliffe formed GEOLA Labs in Vilnius, Lithuania to concentrate on the manufacture of pulsed Neodymium YLF lasers. In May 1992, Mr. Simon Edhouse, joined Australian Holographics as Marketing Manager, becoming General Manager later that year. The company then focused its attention on the international science museum community, selling large holograms to museums in Hong Kong, Singapore, Taipei and Japan. In 1993, Australian Holographics was commissioned by the Sunkung Corporation of South Korea to produce an exhibition of ten large format holograms for Expo '93.

In October 1993, David Ratcliffe relocated to Europe, and handed operational control of the day-to-day running of the Adelaide studios to Simon Edhouse, who managed the marketing and operational aspects of production until the closure of the Australian facility in 1998.

In 1994, Australian Holographics produced a series of holographic billboards for the Singaporean military to promote the 'NS Men' (National Service Men) campaign. The holograms were of the rainbow transmission variety, enclosed in a compact viewing enclosure which housed a mirror to extend the light path for optimal viewing conditions. Also in 1994, Multi Cellular Media Pty. Ltd. trading as Australian Holographics, signed a joint venture agreement with the South Australian Museum, giving the company access to the Museum's vast collection of exhibits.

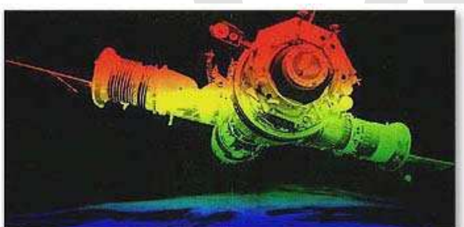
A Holographic Diorama of Extinct Thylacines

One of the first projects undertaken by the new venture was the production of a 1.6 x 1.1 metre rainbow transmission hologram of a family of thylacines. The holographic thylacines, shown standing on a rocky outcrop in a field of dry grass, portrays the now extinct Thylacines as a family group, with the small thylacine pup protruding 50 cm in front of the holographic image-plane.

Frames from a video, panning around the hologram clearly show the horizontal parallax and characteristic blue-green appearance of the Rainbow Transmission hologram.

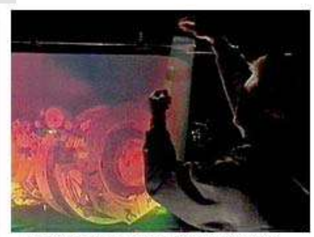
The company also produced a 1.5 x 1.1 metre hologram of a *Tyrannosaurus rex* skull from the S.A. Museum's collection.

In 1995, a large series of holograms were produced of satellites and space vehicles. The most notable of these holograms was the giant 2.1 x 1.1 metre rainbow transmission hologram of the MIR Space Station. This hologram showed a 2 x 3 metre scale model of MIR apparently floating high above the Earth. The model of the Earth used in this hologram was custom made by Adelaide Artist John Haratsis. It measured 4 x 5 x .6 metres resembling a thin slice of a much larger sphere.



Photograph of the finished MIR Rainbow Hologram

Photograph of the custom made 'Earth' model



Handling the exposed holographic film

In 1996, a 'Great White Shark' hologram was produced by the company from a 4.5 metre model made in Queensland by David Joffe. The resulting 1.5 x 1.1 metre rainbow transmission hologram would become the most popular of all the Australian Holographics stock images, being sold around the world to museums, private collections and tourist venues.

Chapter- 10

Diffraction Grating

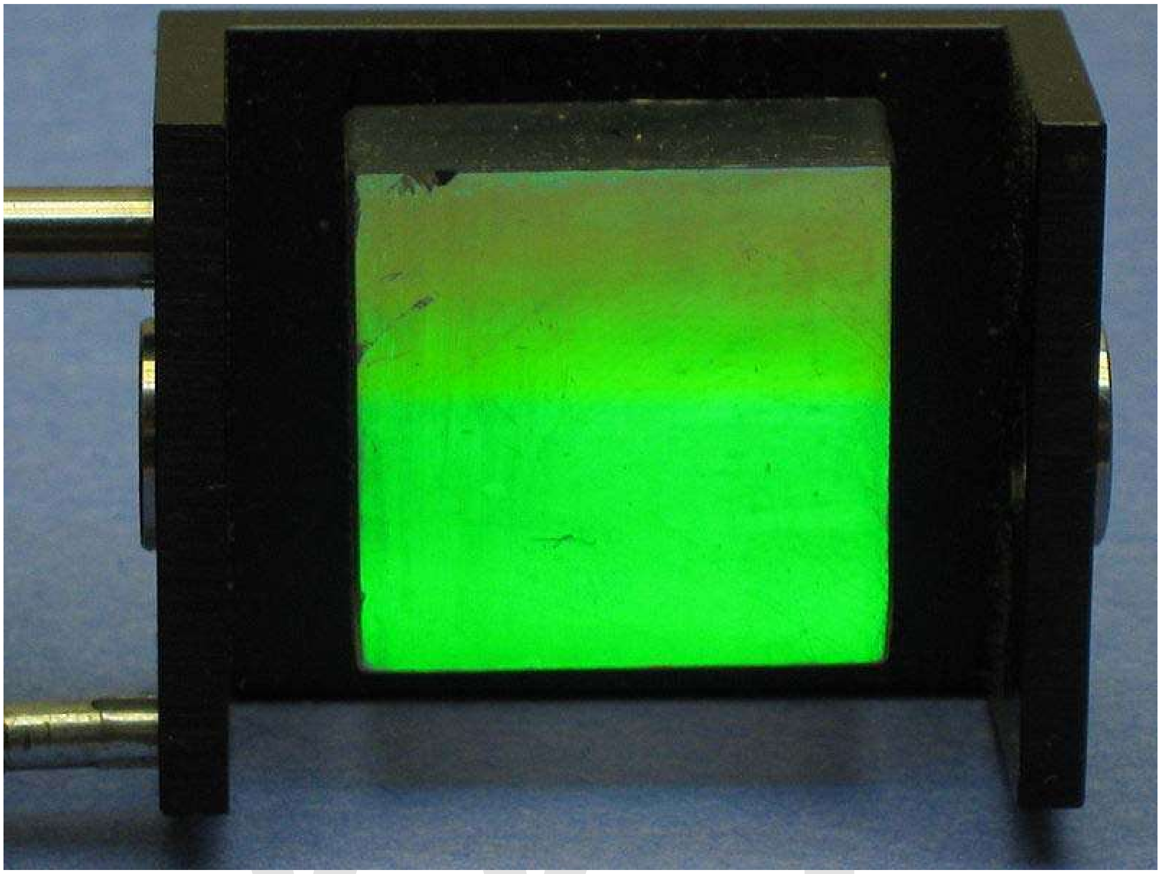
A very large reflecting diffraction grating

In optics, a **diffraction grating** is an optical component with a periodic structure, which splits and diffracts light into several beams travelling in different directions. The directions of these beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as the dispersive element. Because of this, gratings are commonly used in monochromators and spectrometers.

A photographic slide with a fine pattern of black lines forms a simple grating. For practical applications, gratings generally have grooves or *rulings* on their surface rather than dark lines. Such gratings can be either transmissive or reflective. Gratings which modulate the phase rather than the amplitude of the incident light are also produced, frequently using holography.

The principles of diffraction gratings were discovered by James Gregory, about a year after Newton's prism experiments, initially with artifacts such as bird feathers. The first man-made diffraction grating was made around 1785 by Philadelphia inventor David Rittenhouse, who strung hairs between two finely threaded screws. This was similar to notable German physicist Joseph von Fraunhofer's wire diffraction grating in 1821.

Theory of operation



A diffraction grating reflecting green light from a dye laser

The relationship between the grating spacing and the angles of the incident and diffracted beams of light is known as the **grating equation**.

According to the Huygens–Fresnel principle, each point on the wavefront of a propagating wave can be considered to act as a point source, and the wavefront at any subsequent point can be found by adding together the contributions from each of these individual point sources.

An idealised grating is considered here which is made up of a set of long and infinitely narrow slits of spacing d. When a plane wave of wavelength λ is incident normally on the grating, each slit in the grating acts as a point source propagating in all directions. The light in a particular direction, θ, is made up of the interfering components from each slit. Generally, the phases of the waves from different slits will vary from one another, and will cancel one another out partially or wholly. However, when the path difference between the light from adjacent slits is equal to the wavelength, λ, the waves will all be in phase. This occurs at angles θ_m which satisfy the relationship $d\sin\theta_m/\lambda=|m|$ where d is the separation of the slits and m is an integer. Thus, the diffracted light will have maxima at angles θ_m given by

$$d\ \sin\theta_m = m\lambda.$$

It is straightforward to show that if a plane wave is incident at an angle θ_i, the grating equation becomes

$$d\left(\sin\theta_m + \sin\theta_i\right) = m\lambda.$$

The light that corresponds to direct transmission (or specular reflection in the case of a reflection grating) is called the zero order, and is denoted $m = 0$. The other maxima occur at angles which are represented by non-zero integers m. Note that m can be positive or negative, resulting in diffracted orders on both sides of the zero order beam.

This derivation of the grating equation has used an idealised grating. However, the relationship between the angles of the diffracted beams, the grating spacing and the wavelength of the light apply to any regular structure of the same spacing, because the phase relationship between light scattered from adjacent elements of the grating remains the same. The detailed distribution of the diffracted light depends on the detailed structure of the grating elements as well as on the number of elements in the grating, but it will always give maxima in the directions given by the grating equation.

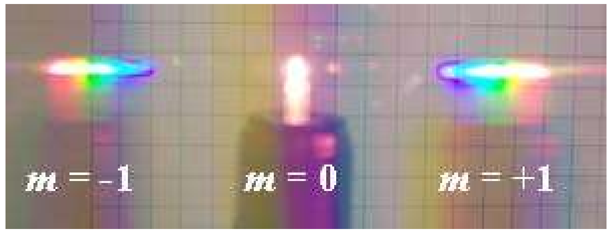
Gratings can be made in which various properties of the incident light are modulated in a regular pattern; these include

- transparency (transmission amplitude gratings)
- reflectance (reflection amplitude gratings)
- refractive index (phase gratings)
- direction of optical axis (optical axis gratings)

The grating equation applies in all these cases.

Gratings as dispersive elements

The wavelength dependence in the grating equation shows that the grating separates an incident polychromatic beam into its constituent wavelength components, i.e., it is dispersive. Each wavelength of input beam spectrum is sent into a different direction, producing a rainbow of colors under white light illumination. This is visually similar to the operation of a prism, although the mechanism is very different.



A light bulb of a flashlight seen through a transmissive grating, showing three diffracted orders. The order $m = 0$ corresponds to a direct transmission of light through the grating. In the first positive order ($m = +1$), colors with increasing wavelengths (from blue to red) are diffracted at increasing angles.

The diffracted beams corresponding to consecutive orders may overlap, depending on the spectral content of the incident beam and the grating density. The higher the spectral order, the greater the overlap into the next order.

The grating equation shows that the angles of the diffracted orders only depend on the grooves' period, and not on their shape. By controlling the cross-sectional profile of the grooves, it is possible to concentrate most of the diffracted energy in a particular order for a given wavelength. A triangular profile is commonly used. This technique is called *blazing.* The incident angle and wavelength for which the diffraction is most efficient are often called *blazing angle* and *blazing wavelength.* The efficiency of a grating may also depend on the polarization of the incident light. Gratings are usually designated by their *groove density*, the number of grooves per unit length, usually expressed in grooves per millimeter (g/mm), also equal to the inverse of the groove period. The groove period must be on the order of the wavelength of interest; the spectral range covered by a grating is dependent on groove spacing and is the same for ruled and holographic gratings with the same grating constant. The maximum wavelength that a grating can diffract is equal to twice the grating period, in which case the incident and diffracted light will be at ninety degrees to the grating normal. To obtain frequency dispersion over a wider frequency one must use a prism. In the optical regime, in which the use of gratings is most common, this corresponds to wavelengths between 100 nm and 10 μm. In that case, the groove density can vary from a few tens of grooves per millimeter, as in *echelle gratings*, to a few thousands of grooves per millimeter.

When groove spacing is less than half the wavelength of light, the only present order is the $m = 0$ order. Gratings with such small periodicity are called subwavelength gratings and exhibit special optical properties. Made on an isotropic material the subwavelength gratings give rise to form birefringence, in which the material behaves as if it were birefringent.

Fabrication

Originally, high-resolution gratings were ruled using high-quality *ruling engines* whose construction was a large undertaking. Henry Joseph Grayson designed a machine to make diffraction gratings, succeeding with one of 120,000 lines to the inch (approx.

47 000 per cm) in 1899. Later, photolithographic techniques allowed gratings to be created from a holographic interference pattern. Holographic gratings have sinusoidal grooves and may not be as efficient as ruled gratings, but are often preferred in monochromators because they lead to much less stray light. A copying technique allows high quality replicas to be made from master gratings of either type, thereby lowering fabrication costs.

Another method for manufacturing diffraction gratings uses a photosensitive gel sandwiched between two substrates. A holographic interference pattern exposes the gel which is later developed. These gratings, called *volume phase holography diffraction gratings* (or VPH diffraction gratings) have no physical grooves, but instead a periodic modulation of the refractive index within the gel. This removes much of the surface scattering effects typically seen in other types of gratings. These gratings also tend to have higher efficiencies, and allow for the inclusion of complicated patterns into a single grating. In older versions of such gratings, environmental susceptibility was a trade-off, as the gel had to be contained at low temperature and humidity. Typically, the photosensitive substances are sealed between two substrates which make them resistant to humidity, thermal and mechanical stresses. VPH diffraction gratings are not destroyed by accidental touches and are more scratch resistant than typical relief gratings.

Semiconductor technology today is also utilized to etch holographically patterned gratings into robust materials such as fused silica. In this way, low stray-light holography is combined with the high efficiency of deep, etched transmission gratings, and can be incorporated into high volume, low cost semiconductor manufacturing technology.

A new technology for grating insertion into integrated photonic lightwave circuits is digital planar holography (DPH). DPH gratings are generated in computer and fabricated on one or several interfaces of an optical waveguide planar with standard micro-lithography or nano-imprinting methods, compatible with mass-production. Light propagates inside the DPH gratings, confined by the refractive index gradient, which provides longer interaction path and greater flexibility in light steering.

Examples

The grooves of a compact disc can act as a grating and produce iridescent reflections

Diffraction gratings are often used in monochromators, spectrometers, lasers, wavelength division multiplexing devices, optical pulse compressing devices, and many other optical instruments.

Ordinary pressed CD and DVD media are every-day examples of diffraction gratings and can be used to demonstrate the effect by reflecting sunlight off them onto a white wall. This is a side effect of their manufacture, as one surface of a CD has many small pits in the plastic, arranged in a spiral; that surface has a thin layer of metal applied to make the pits more visible. The structure of a DVD is optically similar, although it may have more than one pitted surface, and all pitted surfaces are inside the disc.

In a standard pressed vinyl record when viewed from a low angle perpendicular to the grooves, a similar but less defined effect to that seen in a CD/DVD. This is due to viewing angle (less than the critical angle of reflection of the black vinyl) and the path of the light being reflected due to this being changed by the grooves, leaving a rainbow relief pattern behind.

Natural gratings

Diffraction gratings are rarely present in nature. Most commonly confused with diffraction gratings are the iridescent colors of peacock feathers, mother-of-pearl, and butterfly wings. Iridescence is common in birds, insects, and some flowers, and are almost always caused by thin-film interference rather than diffraction. Diffraction will produce the entire spectrum of colors as the viewing angle changes, whereas thin-film interference usually produces a much narrower range. The cell structures in plants and animals are usually too irregular to produce the fine slit geometry necessary for a diffraction grating. However, natural gratings do occur in some invertebrate marine animals, like the antennae of seed shrimp, and have even been discovered in Burgess Shale fossils.