Holography

Holography (from the Greek, *holos* whole + *graphe* writing) is the science of producing holograms, an advanced form of photography that allows an image to be recorded in three dimensions.

**Overview**

Holography was invented in 1947 by Hungarian physicist Dennis Gabor (1900-1979), for which he received the Nobel Prize in physics in 1971. The discovery was a chance result of research into improving electron microscopes at the British Thomson-Houston Company, but the field did not really advance until the invention of the laser in 1960.

Various different types of hologram can be made. One of the more common types is the white-light hologram, which does not require a laser to reconstruct the image and can be viewed in normal daylight. These types of holograms are often used on credit cards as security features.

One of the most dramatic advances in the short history of the technology has been the mass production of laser diodes. These compact, solid state lasers are beginning to replace the large gas lasers previously required to make holograms. Best of all they are much cheaper than their counterpart gas lasers. Due to the decrease in costs, more people are making holograms in their homes as a hobby.

**Technical Description**

The difference between holography and photography is best understood by considering what a photograph actually is: it is a point-to-point recording of the intensity of light rays that make up an image. Each point on the photograph records just one thing, the intensity (i.e. the square of the amplitude of the electric field) of the light wave that illuminates that particular point. In the case of a color photograph, slightly more information is recorded (in effect the image is recorded three times viewed through three different color filters), which allows a limited reconstruction of the wavelength of the light, and thus its color.

However, the light which makes up a real scene is not only specified by its amplitude and wavelength, but also by its phase. In a photograph, the phase of the light from the original scene is lost. In a hologram, both the amplitude and the phase of the light (usually at one particular wavelength) are recorded. When reconstructed, the resulting light field is identical to that which emanated from the original scene, giving a perfect three-dimensional image (albeit, in most cases, a monochromatic one, though color holograms are possible).
To produce a recording of the phase of the light wave at each point in an image, holography uses a reference beam which is combined with the light from the scene or object (the object beam). Optical interference between the reference beam and the object beam, due to the superposition of the light waves, produces a series of intensity fringes that can be recorded on standard photographic film. These fringes form a type of diffraction grating on the film.
Hologram reconstruction process

Once the film is processed, if illuminated once again with the reference beam, diffraction from the fringe pattern on the film reconstructs the original object beam in both intensity and phase. Because both the phase and intensity are reproduced, the image appears three-dimensional; the viewer can move their viewpoint and see the image rotate exactly as the original object would.

Because of the need for interference between the reference and object beams, holography typically uses a laser to produce them. The light from the laser is split into two beams, one forming the reference beam, and one illuminating the object to form the object beam. A laser is used because the coherence of the beams allows interference to take place, although early holograms were made before the invention of the laser, and used other (much less convenient) coherent light sources such as mercury-arc lamps.

Your PhysFest hologram

In this lab you are going to make a transmission hologram, similar to the one described above. The best objects are ones that have interesting depth features but also reflect light well. White objects work best. A toy car is provided with each hologram kit, but you are welcome to try something else. The interference of the object and reference beams is recorded on the photographic emulsion. When the plate has finished its developing process, your hologram can be viewed with a small monochromatic light source, such as the laser or the provided blue LED. To view the hologram, hold the emulsion side toward you and make sure that the light strikes the plate at the same angle that the laser light struck it when you exposed the plate.

Procedure for making a transmission hologram:
The holography instructor in BA 306 will give detailed instructions on how to make your very own PhysFest transmission hologram. In-depth instructions are provided with the hologram kits in lab. The basic instructions are also given here.

1. Arrange your object: Place the clear glass plate and white card into the film holder, leaning forward to rest on the holographic plate support piece. This will approximate the position of the film plate. Place the object in front of the card in the marked area of the plate holder base. Check that the object and white card are illuminated as evenly as possible. You may tilt the laser mount to tilt the laser so that it is aimed squarely at the card.

2. Block the beam: Fold the ends of the black card so it will stand on its own. Place the black card in front of the laser to block the laser beam. This card acts a “shutter” for turning the laser on and off.

3. Arrange the film plate: In the dark room WITH ALL LIGHTS OFF (except for the provided blue LED), open your box of film plates. One side of each plate has a thin, clear coversheet. Through careful inspection using your blue LED, you should be able to easily determine which side has the coversheet. If possible, place the film plate so that the
coversheet faces away from the object. Place the film plate in the long slot on the plate holder, with one edge leaning against the plate support.

4. **Exposure:** Allow the system to settle for at least 3 minutes. Vibrations are the enemy of holograms, so it is important not to talk and to remain as motionless as possible from this point until your hologram is completed. Remove the shutter and expose the film for 5 to 10 minutes. Block the beam again by lowering the shutter.

5. **Completion:** With the shutter in place, blocking the laser beam (after the 5 to 10 minute exposure), remove the object, then remove the shutter to reveal your hologram! Take it home and show off your hard work!
Appendix

Mathematical derivation of
Holographic recording and reconstruction -

Object Wave-function:

\[ E_o(\vec{r},t) = E_o(\vec{r}) \sin(\omega t + \varphi_o(\vec{r})) \]

Here \( E_o(\vec{r}) \) is the amplitude of the object wave at position \( \vec{r} \), and \( \varphi_o(\vec{r}) \) is the phase of the object wave at position \( \vec{r} \). It’s the phase of an object or scene that gives it depth or its “three-dimensional” character.

Normal photography:
Records the intensity of the object wave, not the wave-function itself. The intensity is proportional to the time average of the square of the wave function over many cycles:

\[ I_o(\vec{r}) \equiv 2 E_o^2(\vec{r},t) = 2 E_o^2(\vec{r}) \sin^2(\omega t + \varphi_o(\vec{r})) = E_o^2(\vec{r}) \]

So in regular photography, only the wave amplitude information is recorded, all the object wave phase information is missing – no 3-d character!

Recording the hologram:
Suppose instead we record the intensity of the superposition of the object wave with another, “reference” wave \( E_r(\vec{r},t) \). Then the total wave-function that arrives at the photographic plate (or the film) is

\[ E(\vec{r},t) = E_o(\vec{r},t) + E_r(\vec{r},t) = E_o(\vec{r}) \sin(\omega t + \varphi_o(\vec{r})) + E_r(\vec{r}) \sin(\omega t + \varphi_r(\vec{r})) \]

where we try to choose a reference wave that has a fairly constant amplitude \( E_r \). In general, the amplitude of the object wave, and the phases of both waves, depend on the position \( \vec{r} \), which from now on is to be understood. The intensity that now arrives at the plate is

\[ I(\vec{r}) = 2 E^2(\vec{r},t) = 2 \left(E_o \sin(\omega t + \varphi_o) + E_r \sin(\omega t + \varphi_r) \right)^2 \]

\[ = 2 \left\{ E_o^2 \sin^2(\omega t + \varphi_o) + E_r^2 \sin^2(\omega t + \varphi_r) + 2 E_o E_r \sin(\omega t + \varphi_o) \sin(\omega t + \varphi_r) \right\} \]

\[ = E_o^2 + E_r^2 + 4 E_o E_r \left( \sin \omega t \cos \varphi_o + \cos \omega t \sin \varphi_o \right) \left( \sin \omega t \cos \varphi_r + \cos \omega t \sin \varphi_r \right) \]

\[ = E_o^2 + E_r^2 + 2 E_o E_r \left( \cos \varphi_o \cos \varphi_r + \sin \varphi_o \sin \varphi_r \right) = E_o^2 + E_r^2 + 2 E_o E_r \cos(\varphi_o - \varphi_r), \]

where use has been made of \( \sin \omega t \cos \omega t = 0 \). Thus, the intensity pattern recorded on the plate (the exposure) contains all the phase information of the object wave, relative to the phase of the reference wave. This information is contained entirely in the third term.
which represents the interference between the object and reference wave. The interference term manifests itself on the plate as interference fringes with the spatial period on the order of the wavelength of light. For this reason, good holograms require photographic emulsions with resolutions on the order of the wavelength of light, much higher resolution than is required for regular photographic film.

**Reading the hologram, or object-wave reconstruction:**

After developing the photographic plate we have a medium which is transparent to light with an “amplitude transmittance” proportional to the exposed intensity \( I(\vec{r}) \). Now upon passing the reference wave through the processed plate, the wave that comes through this transparency contains the term:

\[
E(\vec{r}, t) = I(\vec{r}) E_o(\vec{r}, t) = 2 E_o E_r \cos(\varphi_o - \varphi_r) E_r \sin(\omega t + \varphi_r)
\]

\[
= E_r^2 E_o \sin(\omega t + \varphi_o) + E_r^2 E_o \sin(\omega t + 2\varphi_r - \varphi_o)
\]

where we’ve used the identity proved earlier in the quarter:

\[
\sin A + \sin B = 2 \cos \left( \frac{A - B}{2} \right) \sin \left( \frac{A + B}{2} \right)
\]

with \( A \equiv \omega t + \varphi_o \) and \( B \equiv \omega t + 2\varphi_r - \varphi_o \).

By choosing the amplitude of the reference wave to obey \( E_r^2 = 1 \), we find that the first term is an exact reproduction of the object wave, including all the original phase information! The reproduced object wave is seen as a virtual image of the original object, and it propagates in a direction making a large angle from the direction of the reference wave. (This is what allows us to ignore the first two terms in \( I(\vec{r}) \) - these result in a wave in the direction of the reference wave.) The second term is called the “conjugate” wave which is “noise” that propagates on the opposite side of the reference wave from the object wave, and is therefore not seen by the observer of the hologram.