LAB 5: Holographic Interferometry

J-C. Diels and W. Rudolph

Purpose:

Familiarize the student with holography, holographic interferometry, and diffraction gratings.

Reading Assignment

As referenced in text, and Chapter 4 of *Building Scientific Apparatus*, 3rd edition, by John Moore et al. (Perseus Books, Cambridge MA, 2003).

Background

The word hologram was coined from the Greek word "holos" which means whole, because the recorded hologram contains all the information of the image field . Unlike a photograph, which records the square of the electric field, a hologram contains both the amplitude and phase information from the image. Although originally invented by Dennis Gabor in 1948 for the purpose of improving electron microscope images, holography did not attract much interest until the discovery of the laser in 1960.[6] Since then, both artistic and scientific communities have explored the field enthusiastically, finding numerous applications in holographic optical elements (HOE's), optical storage, imaging, and of course, visual arts.

On-axis holography

In Gabor's original work, two waves are superposed on a recording medium as shown in Fig.1.

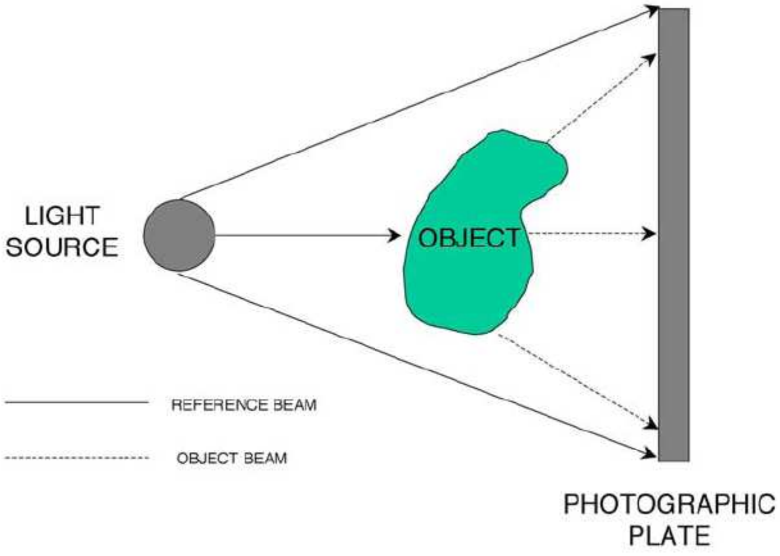

Figure 1. Gabor's scheme for recording a hologram.

A small semi-transparent object is illuminated by a light source. The object scatters the light and creates a second wave which superposes on the recording medium with the reference wave originating from the source. The field on the recording plate can be written as $\mathbf{E}_{\text{total}} = \mathbf{E}_r + \mathbf{E}_o$ where where $\mathbf{E}_r$ is the electric field of the reference wave and $\mathbf{E}_o$ the field of the scattered or object wave. In terms of amplitudes and phases, $\mathbf{E}_{\text{total}}$ can be represented in the following form:

$$\boldsymbol{E}_{total} = [\boldsymbol{E}_r + \boldsymbol{E}_o exp[i(\Psi_o - \Psi_r)]\ exp\{i\Psi_r\}$$

Thus the recorded intensity is

$$I = |E_{total}|^2 = \{E_r^2 + E_o^2 + E_rE_o\ exp[i(\Psi_o - \Psi_r)] + E_rE_o\ exp[-i(\Psi_o - \Psi_r)]\}$$

If the exposure time is T, the amplitude transmittance t of the developed plate is $t = t_o - \beta TI$ where to is the amplitude transmission of the unexposed film. The term E_o^2 contributes to a noise in the reconstruction. This noise is small compared to the reference background E_r^2. If we remove the object and illuminate the developed plate with the original reference beam, the transmitted field will be:

$$\boldsymbol{E}_t = \boldsymbol{E}_r t\ exp\{i\Psi_r\}$$

The field $\boldsymbol{E}_t$ is proportional to:

$$exp\{i\Psi_r\}\ \{E_r + E_o\ exp[i(\Psi_o - \Psi_r)] + E_o\ exp[-i(\Psi_o - \Psi_r)]\}$$

We recognize in the first term the wave which originally illuminated the plate; the second term is identical to the wave scattered by the object. Such a plate which has the property of keeping the amplitude and phase of a wave is called a hologram. The third term is identical to the second except for the phase term $(\Psi_o - \Psi_r)$ which corresponds to a second reconstruction, located on the opposite side of the plate. This conjugate wave which appears during reconstruction, is not seen when we focus on the primary reconstruction. However, its presence degrades the primary wave and prevents getting a high quality hologram. More complete discussions of the theory are available.[2, 6, 7]

Off-axis holography

The technique of holography was improved in 1964 when Leith and Upatnieks proposed the off-axis holography. The experimental set-up for off axis holography is shown in Fig. 2. The beam emitted by a laser is split into two beams. One beam is expanded and sent onto a high resolution recording medium. The second beam is used to illuminate an object. The light scattered by the object interferes in a complex fashion with the reference light. The interferences are recorded on a photosensitive plate. After development of the plate, an object wave can be reconstructed by illuminating the plate with the reference wave at the same angle as for the recording. With this off-axis hologram it is possible to detect the object wave without being disturbed by the reference beam which propagates along another direction. Off-axis holography requires the use of a laser.

Amplitude and phase holograms. A hologram on a photographic plate (with the recording medium of silver halide) is often called an amplitude hologram. The diffraction efficiency (percentage of light in the reconstruction) of an amplitude hologram is very low. It is possible to obtain a transparent hologram with about 10 times higher efficiency by bleaching the plate.

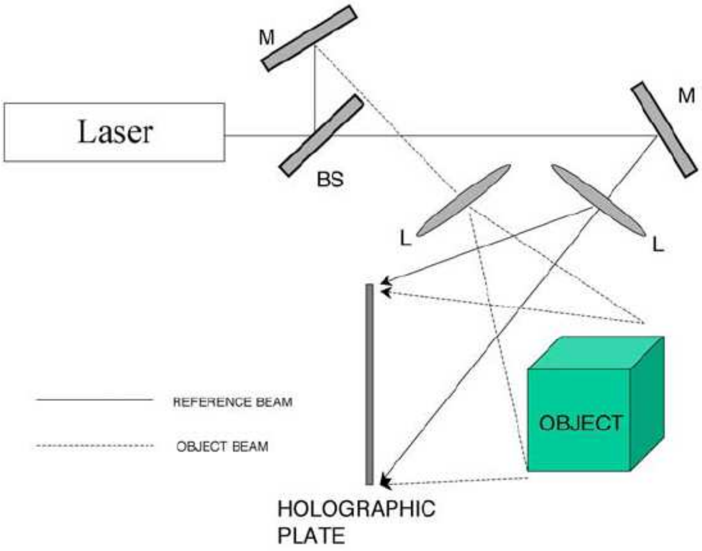

Figure 2. Experimental setup for off-axis holography. (L=lens; M=mirror; BS=beam splitter)

Bleaching is a chemical process which converts the silver image (dark) into a silver salt which is transparent.

Holographic recording. The photographic film consists of a base material (glass, acetate or paper) coated with a suspension of silver halides in gelatin. When the film is exposed to light and developed, the grains of silver halides are changed into metallic silver and the transmittance of the film is altered. If d is a quantity proportional to the amount of the metallic silver, the intensity transmittance (ratio of transmitted light to the incidence light) is given by $\tau = t^2 = Ae^{-d}$ *or* $d = \log(1/\tau) + \log A$.

Film development.

Developing the film is probably the most critical step, and a myriad of developing techniques and recipes exist. The following one is that of T.H. Joeng from Lake Forest College:

Solution A: In 750ml of distilled water (at 100 F) add the following chemicals in order: 20g of Catechol, 10g of Ascorbic Acid, 10g Sodium Sulfite, 75g Urea. When all chemicals have been dissolved add cold water to bring the final solution up to 1 liter.

Solution B: Add 60g of Sodium Carbonate to 750ml of distilled water at room temperature. When disolved, add water to bring the total solution up to 1 liter.

Bleach: In 750ml of distilled water (at 100 F) add the following chemicals in order: 17g Copper Sulfate, 55g Potassium Bromide, 2g Succinic Acid. When all chemicals have been dissolved add cold water to bring the final solution up to 1 liter.

When ready to develop the hologram, mix equal parts of solutions A and B in a shallow tray. This is the developer and will last for up to 8 hours. In a second tray, place some of the bleach. Put the film in the developer for 2 minutes, and constantly agitate the mixture by rocking the tray back and forth. Next, wash the film in running water for 3 minutes. After this, bleach the film (in the bleach solution) until the film is transparent. Then leave it in the bleach solution for an additional 30 seconds. And finally, wash the film again in running water for 3 minutes. At this point it is also a good idea to give the hologram a final rinse in Kodak Photo-Flo (follow the directions on the bottles). This will help the hologram dry evenly without streaking. Before viewing, the hologram must be completely dry. Use a hair dryer to speed up the process.

Experiments

The first requirement for a good hologram is a film with high enough resolution to record the pattern created by the interference of the reference and object beam. You will use Agfa 8E75HD which can resolve 5000 lines per millimeter. The film should be first cut to size in a dark room and then placed between two plates of glass in the provided frame holder. The second requirement is a light source (laser beam) that uniformly illuminates the object to be imaged. Use a spatial filter to clean up and expand the laser beam.

Simple hologram. Produce a hologram of a small object of your choice and read out the image after development. Use the off-axis geometry.

Holographic grating. In this experiment you will produce a holographic diffraction grating. The experimental layout is shown in Fig.3. Two laser beams produce an interference pattern consisting of parallel lines in the plane of the film. Two polarizers in one arm allow you to adjust the laser power while keeping the polarization constant. Measure the intersection angle of the two beams and calculate the line spacing (grating constant) d. Write a grating with the two beams having nearly equal intensity. Write a second grating after attenuating one beam by about 50% with the same exposure time. After developing the hologram evaluate the diffraction pattern produced by the gratings using the unexpanded beam from the HeNe laser. Measure the diffraction angle and compare it to theory. Measure the diffraction efficiency into 1st and 2nd order for both gratings and discuss.

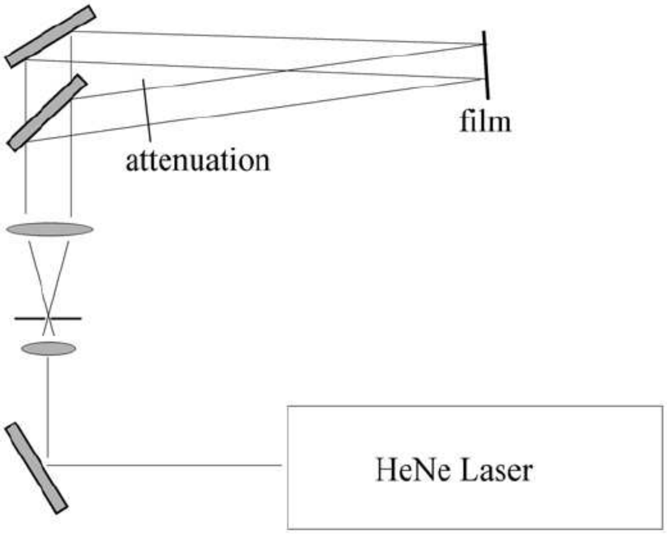

Figure 3. Experimental setup to write a holographic grating

Holographic interferometry. Because holography offers the unique potential to capture the complete electrical field, it is possible to interfere two reconstructed images with each other. This is what is done in a double exposure hologram. In this lab a single exposure will first be taken of an aluminum bar. Then without moving anything, a small weight (20-30 g) will be added to the bar and a second exposure will be made. Since the phase information from both exposures is stored in the hologram, any changes in phase introduced by a small bending (on the order of microns) of the bar will show up as fringes in the reconstructed image. The setup for making such a double exposure hologram is shown in Fig.4, and more information can be found in references.[8]

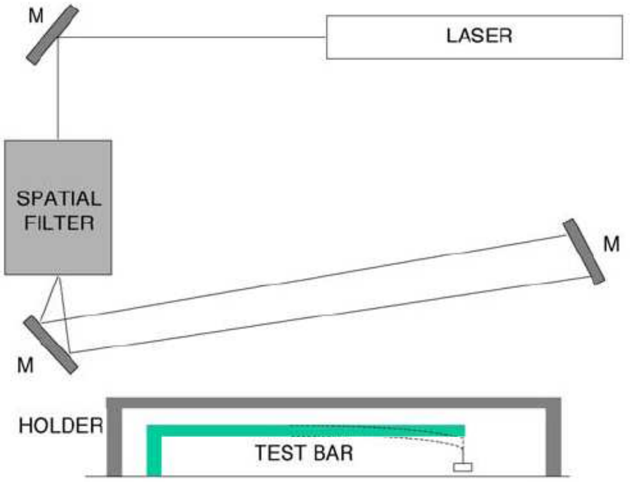

Figure 4. Apparatus for a double exposure hologram.

Upon viewing the developed hologram, one should see a series of fringes crossing the bar (fringes perpendicular to the length of the bar). As might be expected, dark fringes occur where the change in optical path length between the two exposures is equal $n\lambda/2$, where n is an odd integer. If one can assume that for each point along the length of the bar, the displacement due to the extra mass is approximately perpendicular to the surface of the bar, then it is possible to show (you should do this for your report) that fringes will be observed when the displacement Δy is given by:

$$\Delta y = (n\lambda) / \{2(\cos a + \cos \beta)\}$$

Here α and β are the incident angle of the laser light and the angle of observation respectively, both of which are measured from the normal of the surface of the bar, see Figure 5.

Because of the limited coherence length (5 cm) of the laser, you should place the bar as close to the film as possible. Give the entire apparatus some time (2 min) to “settle”. This will allow any small vibrations to damp out, and trapped air to escape from between the two plates. When all is calm, expose the film for about 1 second with the He-Ne laser at full current. (You should verify the correct exposure time by measuring the energy flux at the film with a powermeter and comparing it with the film specifications accompanying this description). Then quickly remove the weight from the bar, wait a few seconds for vibrations to settle and expose the film again for the same period of time.

After developing the film, you will want to carefully measure the spacing between the fringes and use the equation for Δy to calculate the bending of the bar along its length. Compare your results with the theoretical predictions for the bending of a rigid bar due to a force at one end. A description of this situation can be found, for example, in Stephenson's book.[2]

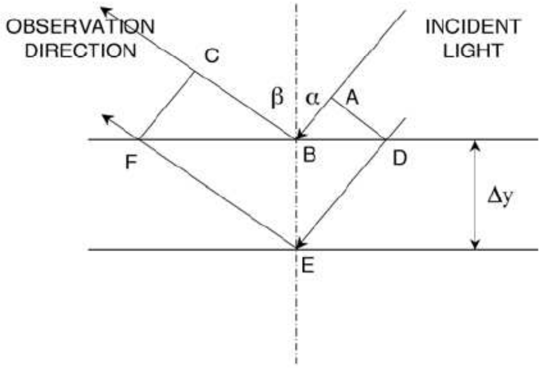

Figure 5. The displacement of the bar due to the additional weight changes the optical path length from ABC to DE. At each small segment of the bar, the displacement is assumed to be perpendicular to the surface of the bar.

Additional Experiments (Optional)

If you have enjoyed your holographic experiment thus far, you may want to continue by making a double exposure hologram of another stressed object. An aluminum can may easily be deformed between exposures by tightening a screw against its side, for example. Another type of experiment involves studying the normal modes of a vibrating object (a handbell driven with a small electromagnet would be a good candidate). In this case only one exposure is necessary, and even though the object is moving during the exposure fringes are still observed. This is because on average the oscillating surface spends most of its time at the two turning points. One then obtains the equivalent of a hologram with an exposure taken at each extremum. Unfortunately, with the more complex geometry an exact analysis of the resulting fringe pattern is not always possible. Another interesting experiment is to produce a Fresnel lens. You can use the basic setup of Fig. 3. Place a lens in one arm so that in the film plane you have a superposition of a parallel and a converging beam. Readout the developed hologram with the expanded parallel beam and search for the focus spot produced by the lens. Measure the focal length and explain.

Summary

1. Produce a simple hologram of a small object.
2. Produce two holographic gratings. Measure and discuss the diffraction efficiency and the diffraction angle.

3. Investigate the bending of a metal bar under the influence of a weight using holographic interferometry. Compare your results qualitatively to theory.
4. Produce a hologram of a vibrating object.

REFERENCES

1. G. Saxby, *Practical Holography* (Wiley, New York, 1988).

2. R. J. Stephenson, *Mechanics and Properties of Matter* (Wiley, New York, 1969).