HOLOGRAPHY

Phys 2010 – Brown University – November 17, 2009

Purpose

The purpose of this experiment is to become familiar with holograms. Specifically, you will learn how to work with laser optics and the techniques of making and viewing holograms.

Laser Safety Guidelines

Out of all the experiments in Physics 2010, the HeNe laser is the most power laser used. You **must** wear laser safety goggles whenever the laser is operating, unless **all** of the following conditions are met:

- The laser tube is properly shielded by the cardboard box.
- The beams coming out of the cardboard box have passed through the variable beam splitter, thus attenuating their intensity.
- The outgoing beams have been dispersed by either the spatial filter or the concave lens.

Introduction

In a conventional photograph, light is reflected off of an object and travels to a piece of film, where the two-dimensional intensity distribution of the light is recorded. . However, the wavefront of the light contains more information about the object than just the intensity distribution. The wavefront's phase also contains information about the object, in the same way that interference patterns contain information about the slit(s) through which they are produced. A hologram, however, is a recording of **both** intensity and phase. The hologram is a diffraction pattern which, when viewed properly, gives a full three-dimensional image of the object.

Principles of holography

Holography is a technique for recording both the intensity and phase profile of light. Because a hologram contains information pertaining to the phase profile of light, it is possible to reconstruct the light based on Huygens' Principle. In the reconstruction process, the light will appear to be coming from the original object, and the three-dimensional aspect of the object will be maintained.

A monochromatic light wave reflected from an object contains all the pertinent information - amplitude and phase - about the object illumination. Ordinary photographic methods only record the intensity of the light across the surface of the object. If the phase information is also to be recorded on the film, we must employ some sort of reference indicating the direction from which the light came. Therefore, holography requires two temporally and spatially coherent light beams, called the object and the reference beam. Temporal coherence is achieved when a wavetrain has one frequency and spatial coherence is achieved when all parts of a propagating wavefront are in step with each other. These concepts will become clear through this laboratory experiment.

To understand the process of holography, we will start with the simplest possible situation - a transmission hologram made by two coherent point sources of light. In this case, we have two waves, which emanate from the two point sources, striking a piece of finely grained photographic film. These two beams, called the object and reference beams, are separated by an angle θ_1. When they arrive at the film, they interfere, constructively in some areas and destructively in other areas. The result of this interference is fringes on the film: bright in regions of constructive interference and dark in regions of destructive interference.

Next, we want to consider the polarization of the object and reference beams. The interference fringes will be sharper if the electric fields in object and reference beams are parallel to each other. When the laser is vertically polarized, the polarization is perpendicular to the plane of the table and parallel to the film for both the object and the reference beams. If the laser is horizontally polarized, then the polarizations of the beams will have an angular separation of θ_2 and will not be parallel to each other or to the film. In general, horizontal polarization leads to less contrast in the interference fringes, because the orthogonal components of the beams do not interfere and, therefore, cause a more homogeneous exposure of the film.

You may wonder how the amplitude and the phase of the object beam are conserved in this process of creating a transmission hologram. For simplicity, think of the laser beam as consisting of many small "beamlets" of constant amplitude, such that when these beamlets first leave the laser cavity, they are perfectly in phase with each other and can be thought of as a plane wave. In this example, after the laser beam is split into the object and reference beams, the reference beam remains a beam of plane waves of constant amplitude through the duration of its trip to the photographic plate. While the object beam is starts its journey from the laser as a beam of plane waves of constant amplitude, when it encounters the object, its beamlets are reflected from the object at various angles and with various intensities. When the object beamlets arrive at the photographic plate, they interfere with the reference beam forming an interference pattern, or grating, as was described earlier. In the places where the object beamlets have the greatest amplitude, the interference pattern has the greatest contrast. In the places where the object beamlets have a smaller amplitude, the there is less contrast or a more even illumination. The angle that the object beamlet is reflected from the object will determine the phase. The *larger* the angle between the reference beam and an object beamlets, the *finer* the resulting grating. Thus, the *amplitude*, or intensity, of the object beam is recorded in the *contrast* of the fringe, while the phase is recorded in the *spacing* between the interference fringes.

Viewing the hologram in ordinary light will reveal nothing about the information contained within. In order to observe the image, the film must be placed in a "reconstruction" or "read out" beam, which is a laser beam identical to the reference beam. The hologram is then viewed from the side opposite to the incoming read out beam. What are transmitted through the film are one zeroth-order beam (the actual read out beam) and two first-order beams. One of the first order beams leaves the film at an angle θ_2. The angle θ_2 is equal to the angle θ_1, where θ_1 is the angular separation between one of the object beamlets and the reference beam. Thus, this first order beam appears, to the eye, to be a continuation of the original object beam. What the eye sees is a virtual image of the point on the object that emitted the particular object beamlet under the angle θ_1. The other first order beam lies at an angle θ_2 on the opposite side of the hologram.

How can we prove that $\theta_1 = \theta_2$ and that all of the phase information is retrieved during the reconstruction process? Think of the reference beam as a plane wave that strikes the film at normal incidence, and the object beam as a plane wave striking the film at an angle θ_1. The wavelength of the laser light is λ, and d is the fringe separation (the distance between regions of maximal constructive interference). So, we can write:

$$\sin\theta_1 = \frac{\lambda}{d}.$$

Therefore, we get that $\lambda = d \sin\theta_1$.

During the reconstruction process, constructive interference occurs when the path difference between two slits, δ is equal to the wavelength of the first order beams. Thus, we get the following:

$$\delta = \lambda = d\sin\theta_2.$$

Thus, it follows that $\theta_1 = \theta_2$. If the wavelength of the reconstruction beam is equal to the wavelength at which the hologram was made, the reconstructed beam leaves the hologram at the same angle that the object beam left the hologram.

Coherence Length

For practical purposes, up to this point, we have considered a laser to be a monochromatic light source, emitting photons of a constant wavelength. In reality, however, the laser beam is comprised of photons that have wavelengths within a narrow band of wavelengths. The bandwidth of wavelengths emitted by the laser is caused primarily due to the mechanics of the laser cavity, not the atomic transitions of electrons in the tube.

The output of a laser relies on standing waves being created within the laser cavity. Thus order for a particular wavelength of light to be emitted by a laser, the length of the cavity inside the laser, L, must be an integer multiple of that wavelength. Noise due to mechanical vibrations and thermal expansion, for instance, can cause the cavity length to vary and thus allow varying wavelengths of light to be emitted. The laser output is a combination of a small number of these longitudinal modes. When these waves combine, they are surrounded by an "envelope" wave with a beat frequency given by:

$$\Delta v = \frac{c}{2L}.$$

This frequency corresponds to a beat wavelength:

$$\Delta\lambda = \frac{c}{\Delta v} = 2L.$$

When a laser beam is split during a holography experiment, this envelope surrounds both the object and reference beams. The two beams have to travel different distances to get to the film. If the difference between the two paths is an even-integer multiple of L (i.e.- 2L, 4L, 6L…) the beams will arrive in-phase, in terms of the envelope, and constructively interfere (in the hologram, the object appears bright at these points). If the path difference is an odd-integer multiple of L (i.e.-: L, 3L, 5L…), the beams will arrive 180° out-of-phase, in terms of the envelope, and destructively interfere (in the hologram, the object will be too dark to be seen). The distance L is called the coherence length, and is denoted by ξ.

Another way of looking at this is as follows: suppose that the laser emits two wavelengths of light, λ_1 and λ_2, with the same amplitude. The frequency difference is given by the TEM_{00q} mode spacing:

$$\Delta v = \frac{c}{2L}, \text{ where } L \text{ is the laser length.}$$

Now, we can split the laser beam and reunite the two beams at a photographic plate. Let's call the difference between the path lengths of the two split beams δ. Consider a point on the photographic plate where the waves at the wavelength λ_1 interfere maximally; a bright fringe will result. We now ask, for what path length difference, δ, will the light of the other wavelength, λ_2, destructively interfere at the same point on the photographic plate? It is obvious that:

$$\delta = n\lambda_1 = \left(n + \frac{1}{2}\right)\lambda_2, \text{ where } n \text{ is an integer.}$$

Thus, we also have:

$$\Delta v = c\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) = \frac{c}{2L}.$$

From the first equation, we can get λ_1 and λ_2, each and in terms of δ. Substituting them into the second equation, tells us that $\delta = L$. In other words, when the path length difference equals the length of the laser, the two wavelengths λ_1 and λ_2, create interference fringes, such that the maxima of the fringes due to λ_1, occur where the minima of the fringes due to λ_2 are and vice versa. Overall, the fringe contrast is very low. Of course, in a real laser, more than two frequencies of unequal intensity occur, but, still, when $\delta = L$, very low contrast fringes are expected.

When a meterstick is used as the object in this experiment, a large range of path lengths is present. Consequently, dark areas are seen (or not seen, rather) where the path length difference is equal to the coherence length, i.e., $\delta = \xi = L$. Thus, in this experiment, the coherence length of a laser, *L* (the length of the laser cavity, or more precisely, the distance between the mirrors in the laser cavity) can be determined through holography.

For more information regarding lasers, please refer to the book, "Lasers" by Anthony E. Siegman.

Equipment

The purpose of the equipment is to produce diffraction patterns, with the spacing of lines being about one wavelength (~6350Å). Any motion of the equipment during exposure will more than likely destroy the diffraction pattern. For this reason, all equipment should be **securely** fastened to the optical bench with bolts or magnetic bases.

- *mW Laser*

- *Shutter:* to block the laser beam when it is not being used.

- *Filter:* to block the blue glow from the discharge tube which would then cause unwanted film exposure. The filter allows the red laser light to pass through relatively unattenuated.

- *Variable Density Beam Splitter:* the density of the metal coating varies with rotation of the beam splitter.

- *Flat Mirror (M1):* vertical and horizontal orientations can be adjusted with knobs on the back.

- *Cylindrical Mirror (M2):* this lens spreads the laser beam in the horizontal direction.

- *Double Concave Lens (L1):* this lens is used to further expand the horizontal beam both vertically and horizontally.

- *Spatial Filter:* it consists of a 10X microscope objective lens and a 25μm pinhole held magnetically. The flat side of the pinhole faces the objective lens. Both components can be adjusted to place the focal point of the objective lens at the pinhole. This apparatus eliminates almost all spurious patterns from other optical components and dust and scratches.

- *Film Holder:* the film is slid into the film frame which is then slid into the film holder.

- *Photometer:* The ratio between the reference and object beams is determined from their readings on the photometer. The detector is highly directional and only reads a small area at a time. The range knob determines the sensitivity and the lower knob (unmarked) allows continuous adjustment of its sensitivity. The higher the number on this lower knob, the more it reduced the sensitivity of the photometer.

- *Holographic Objects:* Meterstick, Soda Can, Soup Can, etc.

Procedure

Please handle the optical components (i.e.: lenses, mirrors, beam splitter) with care. When picking up or adjusting the optical components please hold them by their edges: do not touch the faces of the components with your fingers. If an optical component needs cleaning, please see Bob Horton, he will do this for you; do not attempt to clean an optical component yourself.

Two possible arrangements for the holography experiment are shown in Figures 1 and 2. In Figure 1, the beam transmitted through the beam splitter acts as the reference beam (RB). In Figure 2 the transmitted beam acts as the object beam (OB). Since the transmitted beam is usually more powerful than the reflected beam in a beam splitter, the set up in Figure 2 gives a brighter object overall and therefore less exposure time. However, either set up is acceptable.

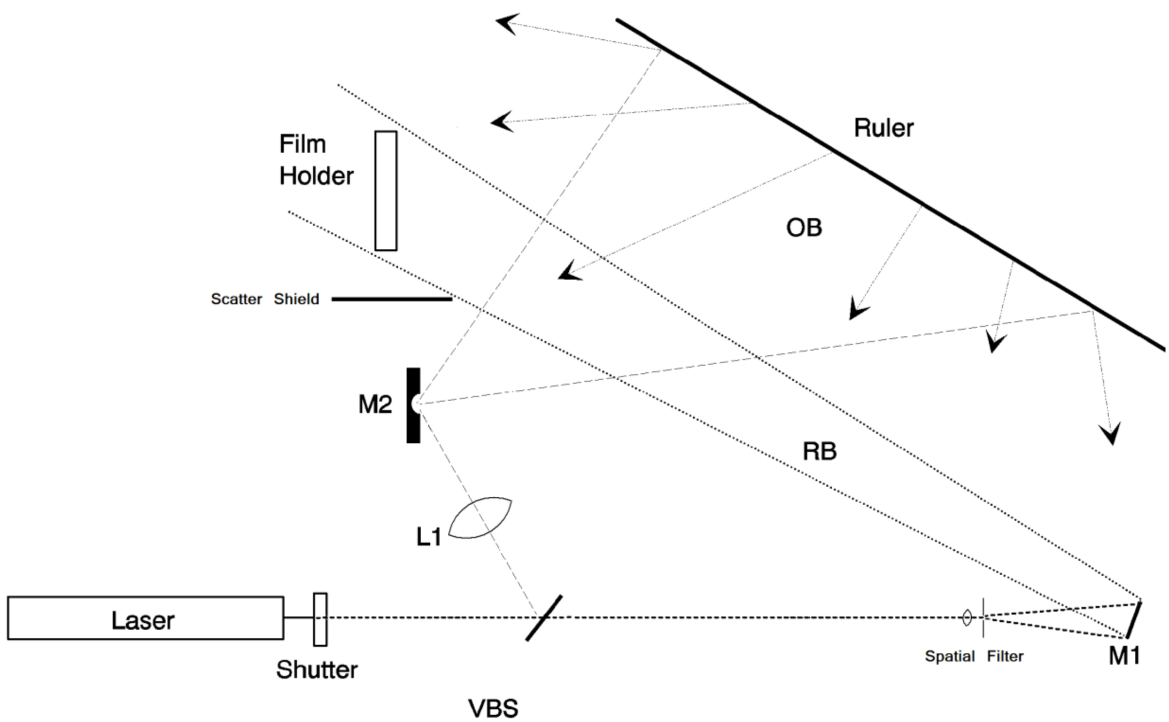

Figure 1. Possible set up for coherence length determination via holography.

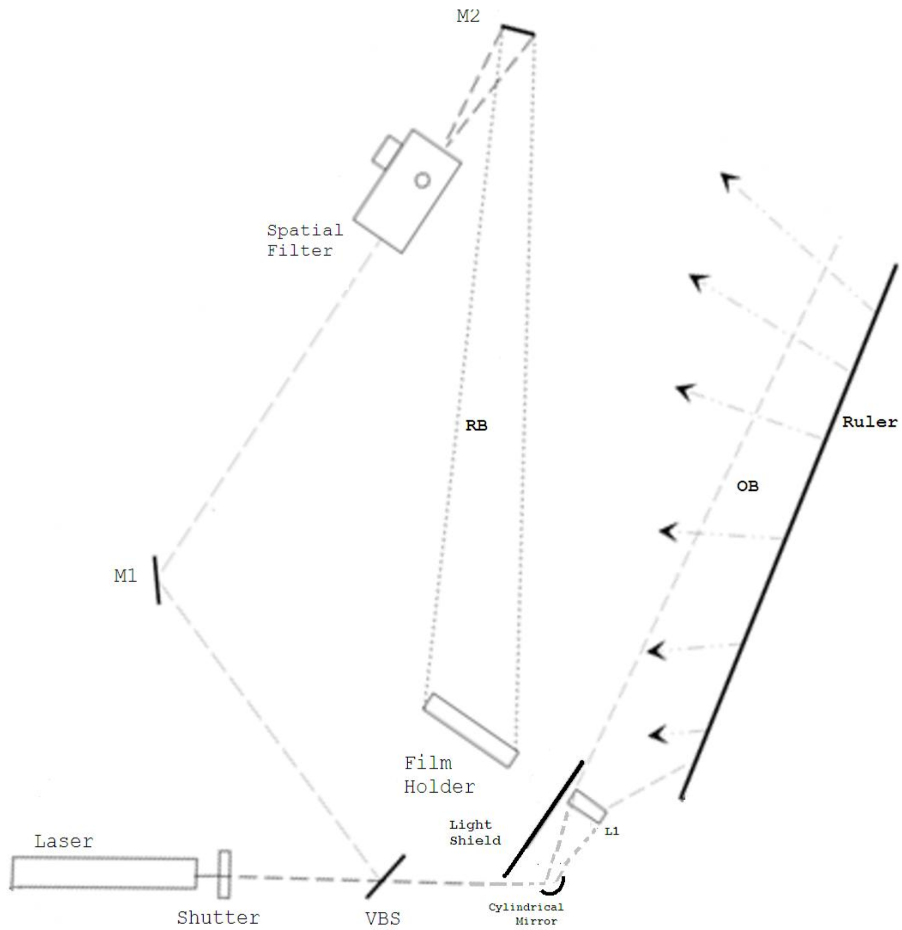

Figure 2. Alternate set up. This would require shorter exposure time, since the object beam is brighter than the one in the set up of Figure 1.

NOTE: Make sure to discuss your setup with either a lab instructor (i.e.: Dean Hudek or Bob Horton) or a TA as you progress though each stage of the experiment.

Spatial filter

Before setting up the all the various components in the experiment, you will need to align the pinhole in the spatial filter.

- The spatial filter follows the variable beam splitter inside the cardboard light shield. Before aligning the pinhole it may be helpful to tape a sheet of paper on the inside of the light shield in front of the spatial filter.
- The laser and spatial filter should already be aligned such that the laser beam passes through the microscope objective along its central horizontal axis.
- Place the pinhole in the spatial filter. It should be oriented such that the *concave* side is facing away from the microscope objective.

- By only touching the outer edge of the variable beamsplitter, set the transmitted light to minimum.

- Defocus the objective in the spatial filter a bit so there is a slightly larger red dot on the back (flat side) of the pinhole.

- While still observing the flat side of the pinhole, adjust the X & Y translations of the pinhole such that the defocused red dot is centered on the pinhole.

- Again, by only touching the outer edge of the variable beamsplitter, set the transmitted light to maximum.

- Observe the white paper you taped to the light shield in front of the spatial filter. Slowly, carefully and methodically adjust the X & Y translations of the pinhole until a red dot appears. When this happens, continue adjusting the X & Y translations until the dot is as bright as possible.

- Once the red dot on the paper is as bright as possible, carefully adjust the Z axis to adjust the focus of the microscope objective. You will likely need to readjust X & Y as Z is adjusted.

- At first the dot on the paper will likely be surrounded by diffraction rings. When the objective is focused in the plain of the pinhole and centered in the pinhole, there will be a large bright area on the paper with no diffraction rings.

- If you have a lot of trouble aligning the spatial filter and spend more then a couple of days trying to align it, please seek help from a TA or lab instructor. If you spend too much time on the spatial filter, you may not have time to finish the lab.

Alignment of components

When arranging your components on the lab bench, it is important to keep in mind that the path lengths of the reference beam and object beam should be fairly equal. The path lengths of the beams are measured starting from the variable beam splitter and ending at the photographic plate. When measuring the object beam length of the meterstick, measure to a point about 10 CM from either end.

- Place the meterstick on two magnetic bases using clamps to hold it in place.

- Place the film holder so that most of the meterstick is visible through the frame. Keep in mind as the other components are placed on the table that the film will be loaded in complete darkness. Try to situate the other components so as to give clear access to the film holder.

- Place a mirror (M1) at the point where the reference beam will be reflected to the film holder. Keep the mirror M1 away from the end of the meterstick; if it is too close to the meterstick, the reference beam will be too close to the object when viewing the hologram and you will risk looking into the beam. This will not hurt you but will interfere with seeing the much dimmer object clearly.

- Make sure the laser is securely fastened in place. If it is not, make sure that all of the screws on the post holders are securely screwed down. Make sure the laser is polarized perpendicular to the plane of the table (i.e. - vertically); this produces better interference fringes. There is a dot on the laser tube which indicates the plane of polarization of the laser beam. If it is not already on the top of the tube, rotate the tube until it is.

- **PUT ON SAFETY GOGGLES BEFORE TURNING THE LASER ON.** Turn the laser on. **It takes about 30 minutes for the laser output to become stable.** Leave the laser on while setting up other components. By the time everything is ready the laser output should be relatively stable.

- The laser beam should be parallel to the optical plane (i.e.: the table). Measure the height of the laser beam at the point it comes out of the box; you can do this using an iris. Move the iris to the far end of the table. The laser beam should pass through the center of the iris; if it does not, then the laser beam is not parallel to the table.

- Adjust the beam splitter so that the weaker beam (RB) goes to M1. The intensity of the beams can be compared either by their brightness or with the photometer.

- Use the cylindrical mirror to direct the stronger beam (OB) to the meterstick. Adjust the mirror so that the beam is centered vertically on the meterstick.

- Place the double concave lens before the cylindrical mirror. The beam will then spread out vertically to cover most of the meterstick. Adjust the cylindrical lens and double concave lenses to get the beam as intense and as even as possible.

- Make sure the laser beam hits the meterstick at the same height along entire the meterstick, after reflecting off of M2. If necessary, adjust M2 and the meterstick until the meterstick is even with the beam. Make sure the laser beam hits film holder in the center after reflecting off of M1. If necessary, adjust M1 and the film holder until the laser beam hits the center of the film holder.

- The laser beam should be centered on each lens and mirror in its path. If it is not, then you should adjust the height of the lens or mirror until it is. Place a white card after each component; the beam should appear even and symmetric, without evidence of diffraction. If not, make adjustments to the components until this is the case.

Path lengths

After all the components are placed as described above, the difference in the path lengths of OB and RB must be taken into account in order to see the coherence length on the meterstick. Generally, an average path length of 100 to 200 cm produces good results.

- First, sketch on a piece of paper where all the components are.

- With a piece of string, measure the distance between each component. When measuring distances to and from your object, make sure to measure from the center of the object. In the case of the meterstick, use the 50 cm mark as a starting point. After the measurements are completed, the total path lengths of the reference beam and the object beam can be calculated.

- The two path lengths should be equal or within 10 cm of each other, as measured near the 50 cm mark of the meterstick. If they are not, relocate the meterstick and the mirrors until the path lengths are as close to each other as possible. If the path lengths of the OB and RB are too different, phase differences due to the finite laser coherence length will occur.

- Next, measure the distance from the double convex lens (L1) to every 10 cm mark on the meterstick. Also, measure the distance from film holder to every 10 cm mark on the meterstick. Using these values, calculate the path length of the OB corresponding to each of the 10 cm marks on the meterstick.

- Now, we can <u>predict</u> where the dark spots due to destructive interference at the coherence length will appear on the hologram. The coherence length will be slightly shorter than the length of the laser tube because the mirror separation is what counts. Since the path length of the reference beam is constant, find the spots on the meterstick where the object beam differs from the path length of the reference beam by one coherence length. There should be at least two such spots on the meterstick, one on each side of the 50 cm mark.

- Adjust M2 so that one or both of these spots is well illuminated.

Reference and Object Beam Ratio

- Use M1 to direct the reference beam to the plate. Make sure the beam illuminates all or most of the film holder. It is acceptable if the beam covers more than the film, this actually this makes the hologram more even.

- Turn off all the lights and turn on the photometer (there is a light switch on the meter that illuminates the scale). Set the range to 4. Block the reference beam with a piece of cardboard and point the detector at the meterstick. Point it at different spots until a maximum reading is obtained.

- Uncover the reference beam and block the object beam. Point the detector at the reference beam and measure its intensity.

- Use the variable beam splitter to reduce the reference beam intensity, until the ratio of the reference beam to object beam intensity is somewhere between 3:1 and 6:1. A typical intensity of the object beam is 20 on the meter with the scale set at 4). One approach, which has been used with success, is to make the OB as bright as possible. It is helpful to maintain similar object beam intensities (for a given object) for consecutive holograms, so that the exposure time will not vary greatly.

- When you are finished using the photometer, turn off the light detector to save the battery in it.

Making the hologram:

- Turn off all the lights in the room and make sure that no light from the lenses falls on the film until you are ready to make the hologram. If necessary, a black cardboard should be used to shield the film holder against stray light.

- Film exposures only take a few seconds, while the entire film processing procedure takes about 20 - 25 minutes. Thus, you can save a lot of time be taking 3 or 4 holograms in a row, and then developing them at the same time.

- Take holograms with different exposure times and different illuminated regions of the meterstick. You initially will want to try a wide range of exposure times: 45 s – 3 min with the low and high ends dependent on your particular setup. Also, make one overexposed (to be bleached) hologram for use with the pinhole experiment.

- After the film has been exposed, it must be developed, washed in water and fixed. Five minutes in each solution is sufficient (rinsing in water between the developing and fixing is essential).

- There are signs posted in the laboratory with general directions for the processing procedure, but you can also contact Bob Horton or Dean Hudek for further details regarding the process.

If the hologram is of good quality, the meterstick will be visible over the range of illumination <u>except</u> for the region where the path length difference is equal to the coherence length which is the length of the laser tube. The image should be clear and bright enough that the numbers on the meterstick are legible and clear. In an exceptional quality hologram, the millimeter lines will be visible.

Reading the hologram:

The hologram can be viewed via two methods:

1. Replace the hologram in the same position as when it was exposed, remove the object, and look at the hologram from behind (being careful not to look at the reference beam). There should be a virtual image in the position the object originally occupied. The reference beam may have to be more intense than it was when the film was exposed.

2. Shine a slightly divergent laser light through the front end of the hologram. An image can be projected onto paper in this way, although only a small area of the hologram may be useful. Shining light through the back end of the hologram produces a magnified image diffracted in the opposite direction. This method is useful for viewing small detail in the picture.

You must take a photograph of your holograph when you have finished making it. Please see Dean Hudek or Bob Horton for a camera.

Experiments

The different experiments are outlined briefly below. Do I and II and either III or IV. If you have time, you may do all four for extra credit. You may use your own digital camera to take pictures of the results (i.e.: the holograms) and include the pictures in your lab report.

Stress Patterns

A single film is exposed twice, but between the exposures the object (a can, for example) is stressed slightly (e.g. by placing a weight on top of it). The areas of the object, which are most easily stressed move appreciably, and if the movement is on the order of a wavelength, the light reaching the hologram from these areas will lead to destructive interference with the previous exposure. After developing the hologram, you will have a picture of the object with a dark line pattern where the object was stressed the most. *Note: The dimensions of object used in this part of the experiment will likely be significantly different than the meterstick used the first part. You should take this into consideration when selecting the mirror used to illuminate the object.*

Coherence Length

As discussed earlier, laser light produced by available lasers is not a pure wave train, but is instead a wave packet with frequencies centered in a small interval around the central value. The group velocity of such a packet may be constant throughout the beam, but the phase velocity varies within the beam. One can define a "coherence length" as the length of beam through which the phase velocity is approximately constant. One can measure the coherence length by using an object, which has a very long extent (e.g., a line of brass bolts in the table in front of the hologram). Different parts of the object give different path lengths for the light, so that if the difference in path length between the reference and some part of the object is greater than the coherence length, there will be no coherence between object and reference beam, and a dimmer hologram will result.

Double Exposure

The film is exposed twice, but the object is changed between exposures to create an illusion (e.g., a pencil through a solid object, such as a can). *Note: The dimensions of object used in this part of the experiment will likely be significantly different than the meterstick used the first part. You should take this into consideration when selecting the mirror used to illuminate the object.*

Wavelength of the Laser Light

An object has laser light incident on it at angle ψ_i, and it is reflected to the hologram at angle ψ_s (see Figure 3).

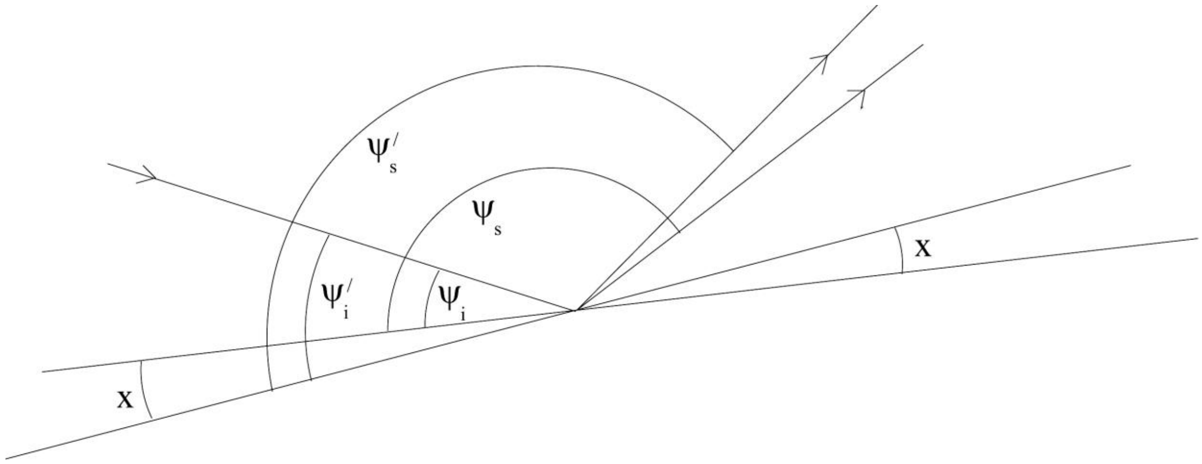

Figure 3. A setup to measure the wavelength of the laser light

The object is then rotated through angle *x* and the hologram is again exposed. When developed, the image will have parallel fringes along the object. The "fringe frequency" or the number of fringes per centimeter *f* is

$$f = \frac{x}{\lambda}\left(\sin\psi_i + \sin\psi_s\right), \text{ where } \lambda = \text{wavelength of laser light.}$$

Two problems must be solved in order to successfully carry out this experiment:

1. One must be able to accurately measure the angles.

2. The film emulsion shrinks when it is developed, giving an image larger than the original. Therefore, one must find a way of measuring the true fringe frequency and not the apparent one.

References

1. Collier et al. *Optical Holography*. New York: Academic Press, 1971. (QC449 .C64)

2. Siegman, Anthony E. *Lasers.* Mill Valley, California: University Science Books, 1986.

3. H.M. Smith. *Principles of Holography*. New York: Wiley-Interscience, 1969. (QC449 .S55)