Holography

Severin Field

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Abstract

It is possible to construct a 3-dimensional image with by recording the interference pattern between a referencing uniform wave and light bouncing off of an object using a photoplate. In this experiment, we created fresnal, fourier and michelson holograms using a high powered Helium-Neon laser. We selected optical arrangements based on calculations for the optical angle between reference and object beams and calculated the optimal exposure time for our arrangements from the vibrational stability of the laser.

I Introduction

Holography can be explained as the interference pattern between two sets of light waves. The interference of waves in water is analogous to light interference - where a greater constructive interference will cause larger crests/troughs and destructive interference will result in shallower crests/troughs. If the medium the wave travels through is moving through is perturbed is perturbed, like wind on the surface of water, the interference will change. If one were to create an interference pattern in water, like clean surfable waves, they'd want to minimize wind. In the same way, creating clear interference patterns with light requires little/no external light interference and silence to prevent the phase from changing and the interference pattern. The photoplates record all wavelengths around 600-700nm so any light including red light needs to be turned off to avoid interference. Single wavelength light sources are also necessary, because light at different wavelengths will appear as random interference. The analogous case with ocean waves illustrates this point: if two ocean waves moving equally fast have differing wavelengths, forming a pattern from them is very difficult! In the making of a hologram, an object is illuminated with laser light and a reference beam of plane waves intersects with it at the photo plate, which is then developed to fix the interference pattern. The hologram captures much more information than a typical photograph, which only records the amplitude and not the phase of light. When viewing a hologram through a photoplate, an observer can move their head and observe parallax. By moving your finger in front of your eyes, you will block different parts of what is in front of you. In a photograph however, moving your head will not change the content of what you are seeing, because it is a 2d portrayal of only the amplitude of light at the time of taking the photo. This is the same reason that on a moving train, telephone poles will fly by while the background mountains will move slowly.

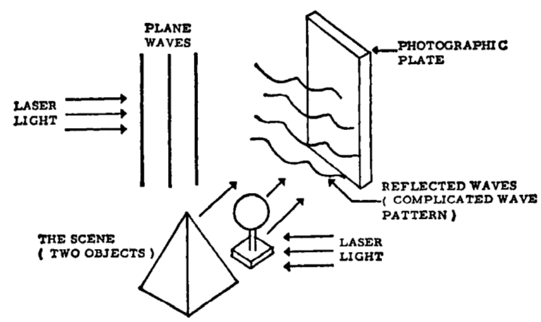

Figure 1: Creating a hologram [1]

Once the photo plate has been developed, the phase and amplitude of the objects interference pattern with the flat plane wave has been recorded, and by viewing the plate with the original reference beam a reconstruction of the object can be seen.

The three types of interference patterns created in this experiment are Michelson interference patterns, from a simple interferometer with a 50/50 beam splitter, a Fourier transform interference pattern, and a Fresnal interference pattern. The latter two use a 90/10 beam splitter and an optical arrangment with an object to create a hologram when reconstructed with a uniform reference beam.

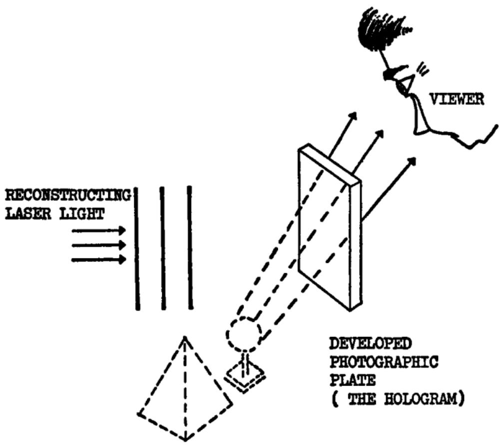

Figure 2: Viewing a hologram [1]

I.I Fourier and Fresnal Holograms

The Fourier and Fresnal holograms are very similar. The Fresnal hologram should act like a diverging lens creating a real image and the Fourier hologram should act like a converging lens creating a real image and a virtual image depending on viewing angle. An optical setup seen below can be used to create a Fourier hologram. Fourier transform mathematics are the summing of infinite sin waves to create any function / image, the mathematics is not necessary for this section.

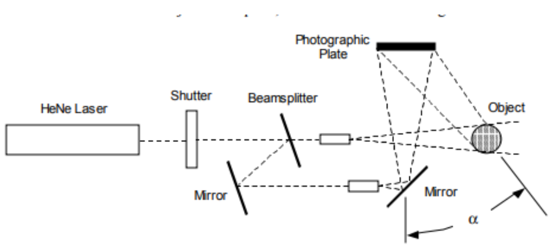

Figure 3: Fourier Transformation hologram optical setup [2]

In a Fourier optical setup, the object is placed equidistant from the photographic plate relative to the reference beam mirror. The angle between the two is α, the angle between object and reference beams. This will be calculated in the next section. A Fresnal setup is similar, with the reference beam further from the photoplate than the object and an objective is placed near the focal point of the reference beam to get the reference beam to behave more like a plane wave.

Our goal is to create both a Fourier and Fresnal hologram and characterize the images we see.

II Experimental Procedure

II.I Setup and Equipment

The vibrational stability of the laser as well as the upper limit to exposure time can be determined using a Michelson interferometer. The optimal exposure time will create a sharp concentric ring in a michelson interference pattern recorded on a photoplate. Below is the diagram for the Michelson interferometer.

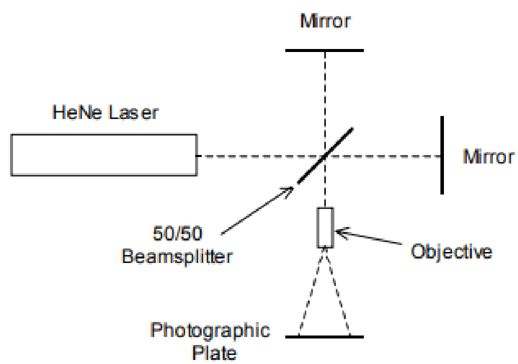

Figure 4: The Michelson interferometer [2]

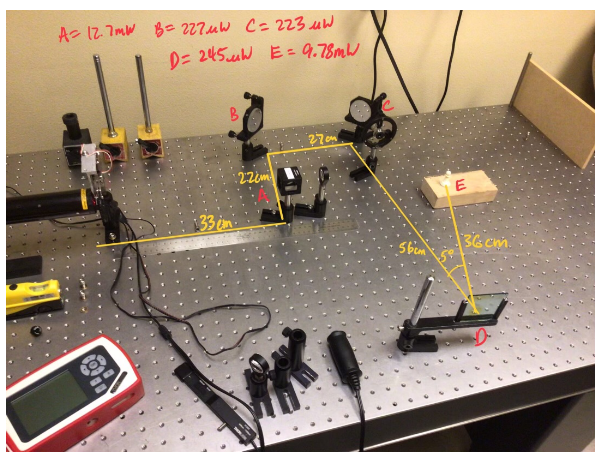

Figure 5: The Fourier Hologram Setup

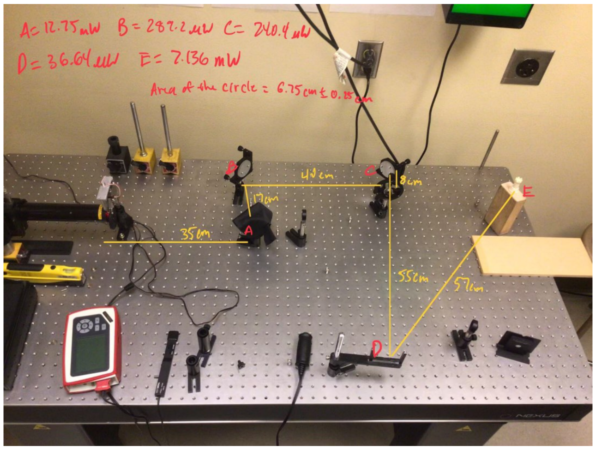

Figure 6: We also tried a second Fourier arrangement. In this one the distance to the object is the same as the distance to the last mirror of the reference beam. This will be referred to as Fourier 2.

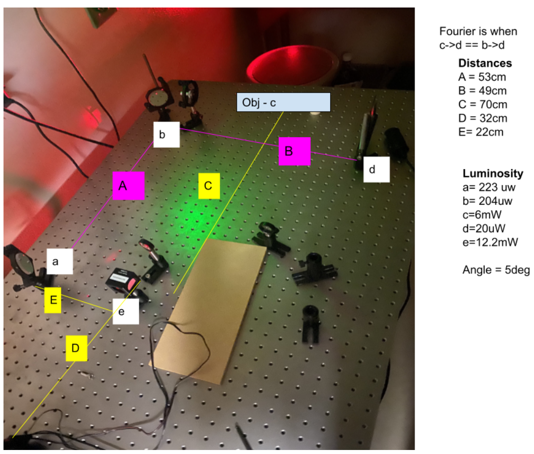

Figure 7: The Fresnal hologram setup

II.II Planar vs. Volume Holograms

A quick aside that will be useful later is the distinction between planar and volume holograms. Volume holograms are where the emulsion thickness of the photoplate largely exceeds the wavelength of light used. These holograms follow Bragg's law and require a threshold angle between the object beam (after bouncing off of the object) and the reference beam. If the angle is greater than this angle, the light reaching the further side of the photoplate will take longer to arrive than the light reaching the near side of the photoplate resulting in a planar hologram.

II.III Calculation of α

Bragg's law can be used to find the optimal mirror angle.

$$d = \frac{\lambda}{2sin(\Theta)} \tag{1}$$

Plugging in the emulsion distance and the wavelength of the laser:

$$6\mu = \frac{832.8nm}{2sin(\Theta)} \tag{2}$$

$$\Theta = 3.97deg \tag{3}$$

II.IV Resolving Power of Hologram

The resolution, or resolving power, can be calculated with

$$R = \frac{1}{d} \tag{4}$$

Where d is the fringe separation through a slit, in this case just the emusion thickness. Our setup has 5000 lines/mm so our resolving power is: 1440 lines/cm.

III Results and Analysis

III.I Exposure Time - Michelson

The max exposure time to create an optimal image can be estimated by looking at the period of intensity as a function of time and finding the period between large vibrations. It doesn't make sense to expose a photo plate for longer than this because a small movement in the beam can translate to a large mistranslation on the photo plate. Using a time interval too short will give you a blurrier image because there isn't enough time for sharp edges to develop because you have a small sample size (relatively) of photons and the distribution of photons cannot be seen properly. However, that doesn't mean that higher exposure is better, because you may be capturing more vibrations, preventing an optimal sharp image. This is because light interference will change drastically with a very small shift, vibration, or noise as discussed in section I. An estimate for the optimal exposure time for this setup can then be determined by shining a beam at a photoplate for varying time intervals and seeing which one shows up most distinct.

The upper limit of the exposure time is 20 seconds. This is gathered from the period of intensity oscillations of the Michelson interferometer. Below is a graph of the intensity vs. time of the Michelson interferometers strongest peak. It's period is roughly 20 seconds so we won't exceed that for our exposure time.

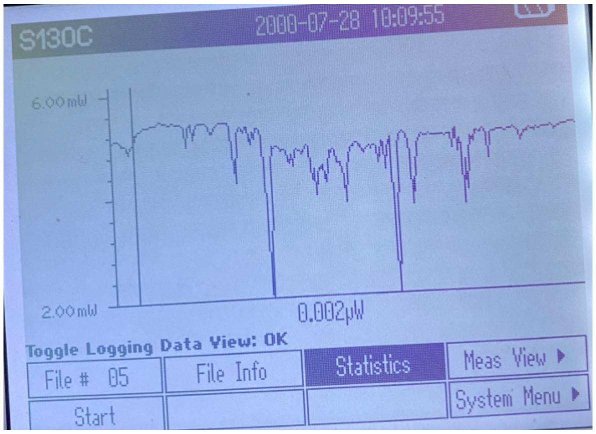

Figure 8: Intensity as a function of time, total time was 1 minute 23 seconds

Next, an interference pattern from the Michelson interferometer is shined onto a photogenic plate to find the optimal exposure time. A more distinct line (wave crest) means the exposure time is moving in the right direction. The 15 second exposure time gave the most distinct crest on the photoplate, this means that 15 seconds is the optimal exposure time. Below is an image of the circular crests, from left to right: 15 second exposure, 10 second exposure, 5 second exposure. We found that a 15 second estimate for exposure time to be the best with the other two interferometer setups as well.

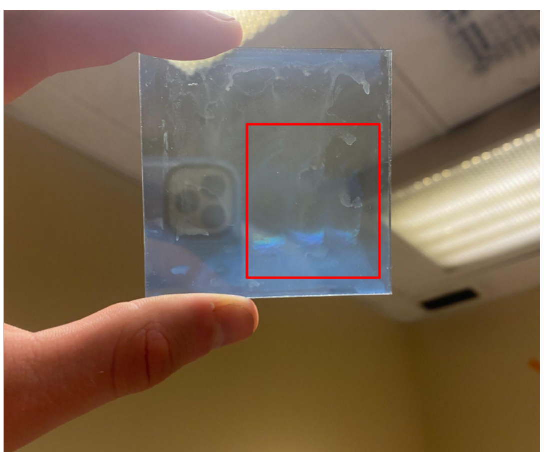

Figure 9: Three crests recorded onto a photoplate with different exposure times

III.II Reference and Object Beam Intensities

Intensity is given by

$$I = \frac{P}{A} \tag{5}$$

The number of photons hitting the photoplate is equivalent to the sum of the number of photons from the reference beam and the object beam that arrive at the photoplate. Therefore

$$I_{total} = I_{reference} + I_{object} \tag{6}$$

Given the 90/10 beam splitter for the Fourier and Fresnal arrangements, we can estimate the power of the object and reference beams. For the Fourier arrangement, the object beam is expected to be 11.47mW and the reference beam should be 1.27mW. This roughly matches our actual values. For the Fresnal arrangement we expect 1.22mW for the reference beams power and 10.98 for the object beams power. This also matches our recorded powers from section II.I. These are the power numbers for after the beam is split, however, the object beams power at point d can be found with equation (8) given the known reference beam power.

The intensity of the object beam on the photoplate can be estimated by taking the power over the area of the light circle that covers the photoplate. In both setups, Fourier and Fresnal, the light circle of the reference beam all falls within the area of the photoplate. The area was measured by placing a solid surface right behind the photoplate and measuring a diameter of approximately 6.75cm. This translates into an area of $35.9cm^2$. The area of the light reflecting off of the object beam encompasses is the entire photoplate, or roughly $56.2cm^2$.

The expected intensities for the Fourier arrangement are:

$$I_{reference-estimate} = .035\frac{mW}{cm^3} \tag{7}$$

$$I_{object-estimate} = .015\frac{mW}{cm^3}(eq.8) \tag{8}$$

The measured values are:

$$I_{reference-actual} = .0240\frac{mW}{cm^3} \tag{9}$$

$$I_{object-actual} = .002\frac{mW}{cm^3} \tag{10}$$

A couple of things could be happening here - where the photoplate doesn't pick up the green light, the detector likely does, this could be adding to our measured values (or adding to the expected values since they were calculated with power reading values). Another explanation as to why these don't match perfectly is the high level of oscillation in the power meter readout. Finally, if the object that we reflected light off of was moved to scatter light differently, it could drastically affect how much object-light reaches the photoplate.

Next, for the Fresnal arrangement, the expected and actual intensities are:

$$I_{reference-actual} = .0204\frac{mW}{cm^3} \tag{11}$$

$$I_{object-actual} = .012\frac{mW}{cm^3} \tag{12}$$

$$I_{reference-estimate} = .033\frac{mW}{cm^3} \tag{13}$$

$$I_{object-estimate} = .013\frac{mW}{cm^3} \tag{14}$$

III.III Contrast Ratio

The dynamic contrast ratio is the ratio between the brightest intensity received vs. the darkest. This can be taken as the ratio between the highest peak in the intensity over time curve divided by the shallowest dip.

$$C_{dynamic} = I_{max} : I_{min} \tag{15}$$

The dynamic contrast ratio for the Fourier arrangement (number two) is roughly 39:35. For the Fresnal arrangement, this ratio is 19:12.

The static contrast ratio is the ratio between the brightest spot in an image and the darkest spot. This is calculated by

$$C = I_{reference} - Iobject \tag{16}$$

At the point of the photoplate.

The static contrast ratio for the Fresnal arrangement is 3.13 and the contrast ratio for the Fourier arrangement (number two) is 4.29.

III.IV Images

We took quite a few pictures of the holograms we generated. The pictures fail to show the parallax affect because they're two dimensional, the resolution is also not ideal.

The object that we capture is a rook game piece from chess.

Figure 10: The first image from the Fresnal hologram, a fairly distinct virtual image around the location of the object

There are two images from each hologram, however the virtual image on the side of the rook is more distinct from both our Fourier and Fresnal arrangements. There is an upright virtual image and a second real image that looks upright as well, but is harder to see. The Fourier arrangement creates two virtual images, one chess piece sized image around the location of the chess piece and one inverted virtual image which is much smaller on the other side of the photoplate. The size of the image is a direct consequence of the distance from the focal point, if the focal point from the light reflected off the object is closer, the image will appear bigger and vise versa. This effect seems to be the opposite for the smaller inverted image.

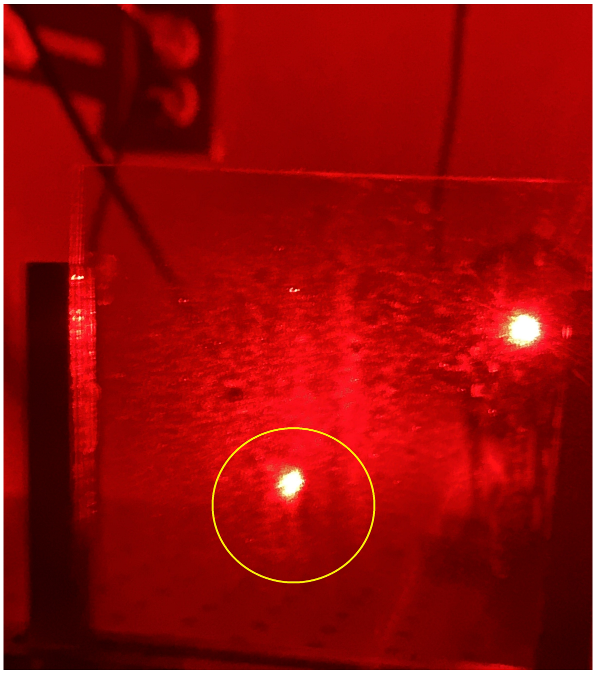

Figure 11: The second image from the Fresnal hologram

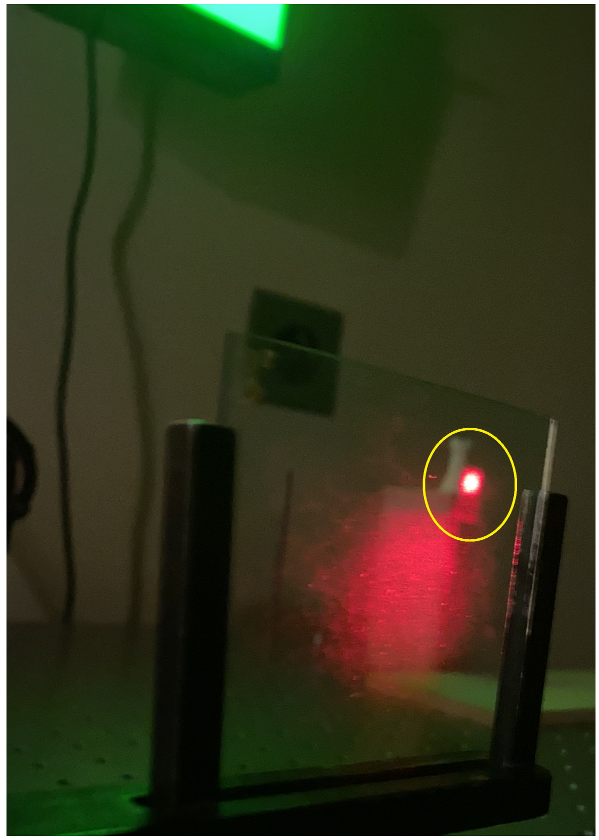

Figure 12: The first image from the Fourier setup

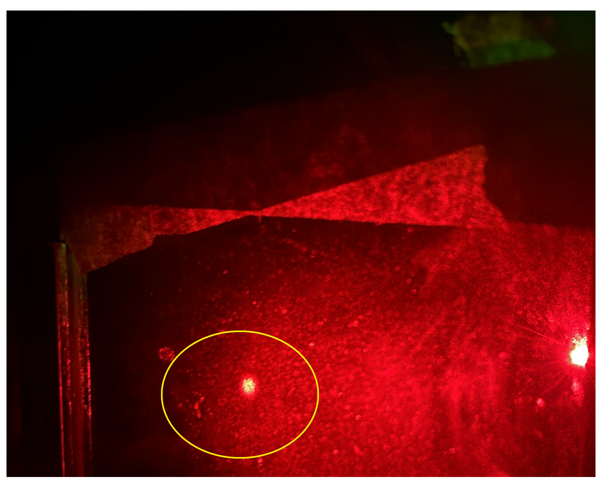

Figure 13: The second image from the Fourier setup

IV Conclusion

During this experiment, we were able to create 3-d parallax holograms by recording the interference pattern of two sources of light: one bouncing off of an object, and one planar reference beam. We recorded a number of both Fourier and Fresnal holograms and included in this paper are the most clear pictures of them. We also measured and accounted for constraints that affect image quality such as the contrast ratio, optimal exposure time and the optimal angle between the object and the reference beam. If we had more time, I would've liked to investigate other different types of holograms.

References

[1] E. Kock, *Lasers and Holography: An Introduction to Coherent Optics*. New York: Dover, 1981.

[2] D. Beyermann, "Holography manual," *UC Riverside*, 2022.