# PHYS3114 – Holography


J.J. Whittaker (z5363798)[1,2]
[1] *Thursday B 2-6 Class*
[2] *Word count: 4285 words*

(Dated: 15:00 Thursday 1st Nov 2023)


This experiment explores the formation and reconstruction of phase holograms. It showed the nature and difference between reflection and transmission holograms in their formation and reconstruction. Reflection holograms can be reconstructed in incoherent light due to its minimal dispersive effects while transmission holograms are extremely sensitive to the wavelength bandwidth of the light for reconstruction. The experiment enforces the mathematical representations of both scenarios as the inclusion of a wavelength term in the transmission hologram reconstruction field creates the observed sensitivity to chromatic coherence. The double exposure holographic interferometry created a physical representation of strain in an object through interference fringes across its body and the Michelson Interferometer showed the interference pattern from a phase difference caused by differing path lengths.


## INTRODUCTION

The language of Phase Holography is the language of Scalar Optical Wave Functions as they allow the treatment of the phase and amplitude of multiple interfering fields. This is due to the time harmonic components of the wave function oscillation speed being significantly faster than the response time of the medium.

An optical wave has the representation;

$$U(r,t) = Ae^{i(kr-\omega t)}, \tag{1}$$

And the corresponding intensity of the wave has the representation;

$$I(r,t) = U(r,t)U(r,t)^* = |A|^2. \tag{2}$$

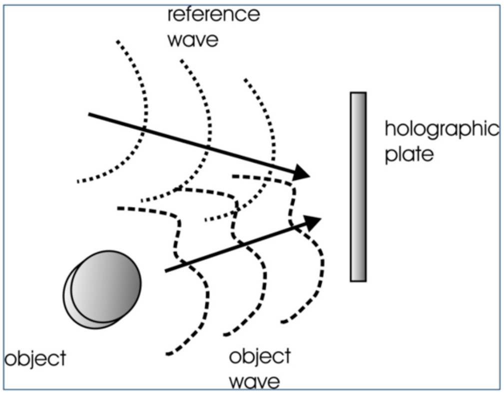


FIG. 1: Idealised scenario for holographic recording.

Let two coherent waves incident on a plate (seen in FIG. 1) be $a(x,y) = |a(x,y)|e^{i\varphi(x,y)}$ the object wave, and $A(x,y) = |A(x,y)|e^{i\psi(x,y)}$ the reference wave. Thus, the total intensity on the plate is given by;

$$I(x,y) = |A(x,y)|^2 + |a(x,y)|^2 + 2|A(x,y)||a(x,y)|cos\left(\varphi(x,y) - \psi(x,y)\right). \tag{3}$$

The phase information of the wave is now contained within the intensity profile at the plate.

A holographic film is a photosensitive recording medium which stores this field by chemically altering the refractive index of the film. The refractive index is a function of position and acts as interfering diffraction gratings that when exposed to light can reconstruct the field that was imprinted onto it.

The recorded film transmission becomes;

$$t_A(x,y) = t_b + \beta'[|a(x,y)|^2 + A(x,y)^*a(x,y) + A(x,y)a(x,y)^*], \tag{4}$$

where $\beta'$ is some relative response of the media.

By supplying a coherent reconstruction beam, $B(x, y)$, the transmitted field becomes;

$$B(x,y)t_A(x,y) = t_b B + \beta' a a^* B + \beta' A^* a B + \beta' A a^* B, \tag{5}$$

or in the simple case where you are reconstructing the hologram with the same light that is used to expose it;

$$\beta' |A|^2 a(x,y), \tag{6}$$

which is just a scaled version of the object wave, a reconstruction of the object.

The analysis done above is for reflection holograms for when the incident and reflected waves are either parallel or perpendicular. A transmission hologram is when the reference beam and object beam are incident on the holographic plate at different angles. The mathematical representation of these waves is the following;

$$U(x,y) = A\, exp\left(-i2\pi y \frac{\sin(2\theta)}{\lambda}\right) + a(x,y), \tag{7}$$

with a given intensity;

$$I(x,y) = \left(|A| exp\left(-i2\pi y \frac{\sin(2\theta)}{\lambda}\right) + a(x,y)\right)\left(|A| exp\left(+i2\pi y \frac{\sin(2\theta)}{\lambda}\right) + a(x,y)^*\right). \tag{8}$$

The beam upon reconstruction with some $B(x, y)$ then becomes;

$$\beta' B A^* a(x,y) exp\left(i2\pi y \frac{\sin(2\theta)}{\lambda}\right), \tag{9}$$

$$\beta' B A\, a(x,y)^* exp\left(-i2\pi y \frac{\sin(2\theta)}{\lambda}\right), \tag{10}$$

for real and virtual images respectively. The main difference is the addition of a wavelength term which is the main point of exploration for this laboratory.

(The content of this introduction can be found in [1])

## METHOD

### Experiment 1: Denisyuk Hologram

1. Verify the output power from the laser is 2 mW.
2. Mount a mirror at the end of the table to reflect the beam by 90°.
3. Place and align the spatial filter (non-trivial) in the path of the reflected beam.
4. Place the plate holder perpendicular to the incoming light such it is fully illuminated within the light.
5. Use a power meter to estimate the power of the light at the plate holder (assume the plate is uniformly illuminated)
6. From the measured intensity, estimate the exposure time required remembering the light during exposure will be 108 times as intense. (double exposure time due to age of holographic plate)
7. Place the object directly behind the plate holder such it is centred with respect to the plate.
8. Place light baffles around the object to reduce any bright spots that may affect the exposure.
9. Dim the lights and place an unexposed plate within the plate holder ensuring the photosensitive film is facing towards the object.
10. Use the interlock to exit the room and start the exposure.

(The experimental setup can be found in Holography Student Operating Notes Figure. 1 [2])

### Experiment 2: Transmission Hologram

1. Use the same setup in Experiment 1 steps 1 – 3.
2. Place the plate holder 45° with respect to the incoming light such it is fully illuminated within the light.
3. Place the object such it is centred with respect to the plate but far enough away such the object does not interact with the incident light.
4. Place the beam splitter before the original mirror, directing the reflected beam parallel to the original beam.
5. Vary the beam splitter such the ratio of transmitted and reflected beam is 4:1.
6. Use a mirror to direct the secondary beam towards the object such it reflects off the object towards the plate (This does not need to be exact). In this case, the incident and object light are not perpendicular.
7. Place the Aspheric lens in the path of the reflected beam to fully illuminate the object.
8. Measure the intensity of the incident light at the plate and measure the intensity of the reflected light at the object. The sum of theses intensities is the power measurement used for exposure time calculations. As the beam has been split, the exposure time will need to be doubled.
9. Dim the lights and place an unexposed plate within the plate holder ensuring the photosensitive film is facing towards the object.
10. Use the interlock to exit the room and start the exposure.

(The experimental setup can be found in Holography Student Operating Notes Figure. 2 [2])

### Experiment 3: Double-exposure holographic interferometry

1. Use the same setup as Experiment 2 steps 1 – 8.
2. Replace the object with the can ensuring the object holder is solid (solid enough to assume to be perfectly rigid.)
3. Place the weight on top of the can.
4. Using the previously calculated exposure time, the ratio of the first exposure to second exposure should be 1:4.
5. Dim the lights and place an unexposed plate within the plate holder ensuring the photosensitive film is facing towards the object.
6. Use the interlock to exit the room and start the first exposure.
7. Return to the object and carefully remove the weight.
8. Use the interlock to exit the room and start the second exposure.

### Experiment 4: Reflection hologram

1. Start with the same setup as Experiment 2 steps 1 – 8.
2. Place the object behind the plate holder such it is centred with respect to the plate.
3. Vary the beam splitter such the ratio of transmitted and reflected beam is 2:1.
4. Configure the secondary mirror to direct the reflected beam towards the object such it reflects off the object towards the plate. In this case, the incident and object light should be setup such they are perpendicular.
5. Place the Aspheric lens in the path of the reflected beam to fully illuminate the object.

6. Measure the intensity of the incident light at the plate and measure the intensity of the reflected light at the object. The sum of theses intensities is the power measurement used for exposure time calculations. As the beam has been split, the exposure time will need to be doubled.
7. Dim the lights and place an unexposed plate within the plate holder ensuring the photosensitive film is facing towards the object.
8. Use the interlock to exit the room and start the exposure.

(The experimental setup can be found in Holography Student Operating Notes Figure. 3 [2])

**Experiment 5: Michelson Interferometer**

1. Remove all components from the working area.
2. Place a mirror (M1) into the beam directly from the laser, such to reflect the beam 90°.
3. Place the beam splitter in the path of the reflected beam as to reflect the beam anti-parallel to the beam originating from the laser.
4. Place a mirror (M2) in the path of the anti-parallel beam, reflecting the beam back exactly towards the beam splitter.
5. Place a mirror (M3) in the path of the perpendicular transmitted beam from the beam splitter, reflecting the beam back exactly towards the beam splitter.
6. This should be adjusted such all light entering and exiting the beam splitter is incident on a single point.
7. The combined beams will in turn be directed parallel to the direction of the beam originating from the laser.
8. Place a screen in the path of the combined beams.
9. Place an Aspheric lens in the path of the combined beam to illuminate the screen.
10. Observe the fringes on the screen.
11. The path length of the individual beams should be adjusted to maximise the fringe separations.
12. Observe the behaviour of the fringes during a perturbation of the airflow is, or when small vibrations are placed on the system.

(The experimental setup can be found in Holography Student Operating Notes Figure. 4 [2])

## RESULTS & ANALYSIS

### Experiment 1: Denisyuk Hologram

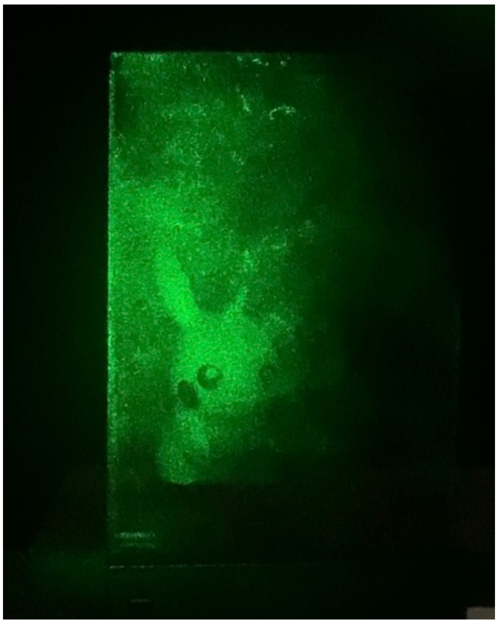

FIG. 2: Photo of the Denisyuk Hologram illuminated by the low-intensity exposure light.

The intensity of the light at the plate was measured to be 41.1 $\mu W$ at the centre of the plate during low exposure. The intensity at exposure was 108 times this intensity thus the intensity taken for exposure time calculations is;

$$P_{exp} = (108)(0.0411) = 4.438\ mJ\ s^{-1}. \tag{11}$$

The given aperture size for the photo diode was $d_{app} = 0.95\ cm$ thus the power density per $cm^2$ is calculated by;

$$p_{exp} = \frac{4.438}{\frac{\pi(0.95)^2}{4}} = 6.261\ mJ\ s^{-1}\ cm^{-2}. \tag{12}$$

The exposure energy for the plate under green (532 nm) light is 30 $mJ\ cm^{-2}$ [2]. Thus, the theoretical exposure time is;

$$t_{exp} = \frac{30}{6.261} = 4.79\ s\ \approx 5\ s. \tag{13}$$

To ensure a sufficient exposure this time is doubled thus;

$$t_{exp} \approx 10\ s. \tag{14}$$

*The calculations at the time did not consider the aperture size of the photo diode and such the theoretical exposure time that was used was taken as $t = 6.76\ s\ \approx 7\ s$. This was also mistakenly increase by a factor of 3 instead of 2 thus the final exposure time was $t = 20\ s$. This would have overexposed the plate, but this did not considerably affect the hologram.*

The resulting hologram (FIG. 2) was visible and clear and could be seen under the low-intensity coherent exposure light and in non-coherent light from a lamp or sunlight. (It blew our minds)

1. **How is the information about the scene / object captured by the plate?**

Unlike other recording media which normally only respond to light intensity, the holographic plate responds to the phase of the interference of the incident and object light. In turn it captures the phase response of the object field. The photosensitive recording media reacts to the light at a certain intensity and creates a series of diffraction gratings which when illuminated in the absence of the object, recreates the objects field. This is done as the refractive index of the recording medium varies with position, imposing a phase modulation onto the illuminating beam.

2. **Why is this considered a volume hologram?**

A volume (thick) hologram is a hologram where the thickness of the recording media is much larger than the wavelength of the light used for recording. The thickness of the photosensitive film is $16\ \mu m = 16000\ nm$. The wavelength of the light used is $532\ nm \ll 16000\ nm$.

**3. What are the coherent requirements for the light source in recording this type of hologram?**

The recording method of the plate uses the interference between the incident and reflected light. This is highly sensitive to phase differences and thus a coherent light source must be used. Temporal coherence is the intrinsic bandwidth of the light and if such bandwidth is large, the hologram produced will be blurred due to the overlapping diffraction 'gratings' produced by the exposure.

**4. Why is it that you can use an incoherent light source to read out the hologram?**

The fringes created within the recording media are oriented parallel to the surface of the film which has the effect of only interacting with specific wavelength of light it was produced with and letting other wavelengths transmit un-perturbed. Thus, an incoherent light source which contains the recording wavelength (a white light i.e., sunlight) will reconstruct the hologram. This can also be seen in the mathematical representation of the reconstructed field;

$$t_b B + \beta' a a^* B + \beta' A^* a B + \beta' A a^* B, \tag{5}$$

Which is not modified under an addition of a different wavelength light.

In contrast, the mathematical representation of the reconstructed field of a transmission hologram is modified under the addition of a different wavelength seen;

$$\beta' B A^* a(x, y) \exp\left(i 2\pi y \frac{\sin 2\theta}{\lambda}\right). \tag{9}$$

**5. Why is it that the hologram changes colour when the viewing angle is modified?**

There is a small bandwidth of light that is produced by the laser as it cannot be perfectly coherent. The different wavelengths of light interfere constructively and destructively to each other and thus at different viewing angles, other wavelengths of light can appear. This was not apparent when viewing the produced hologram thus the conclusion is that the light from the laser used was sufficiently coherent. (I am not too sure about this, it also could be that at some viewing angles, the diffraction 'gratings can constructively interfere with other wavelengths of light from a non-coherent light source, i.e. the Bragg Effect)

**6. Explain the basic properties and physical origin of the pseudoscopic image, which is observed when the hologram is viewed from the reverse side of the plate.**

The effects of viewing the image from the opposite side include an inverted perception of depth where the image forms in front of the plate, an inverse parallax effect, where moving the plate to the left causes a shift in the image to the right. For the physical origin of these effects, when viewing the hologram from the reverse side, the angles of incidence and reflection are effectively reversed causing the inverse parallax effect. For the inverted depth perception, viewing from the back side causes the wavefronts of the object and reference beams to reverse. It reconstructs the image as if the object and reference beams were reversed.

**Experiment 2: Transmission Hologram**

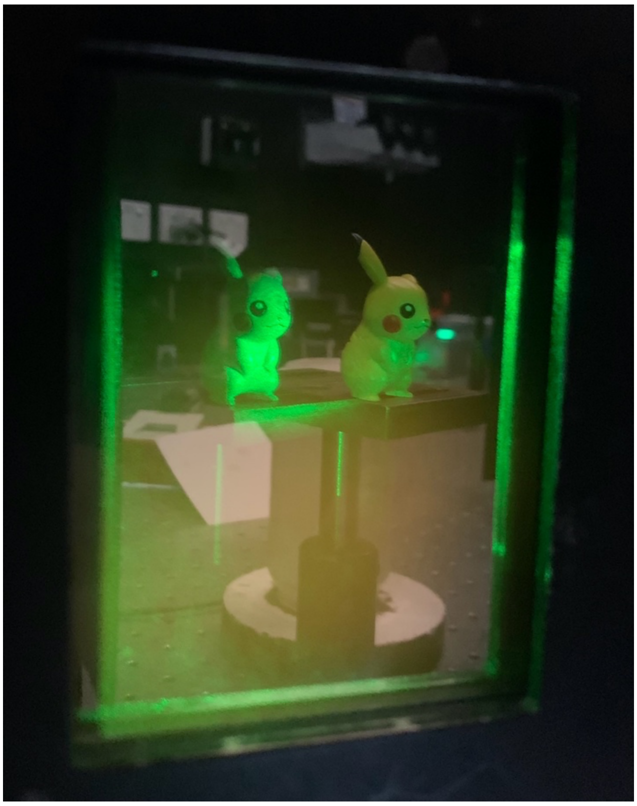

FIG. 3: Photo of the Transmission Hologram illuminated by the low-intensity exposure light showing the original object moved to the side for reference.

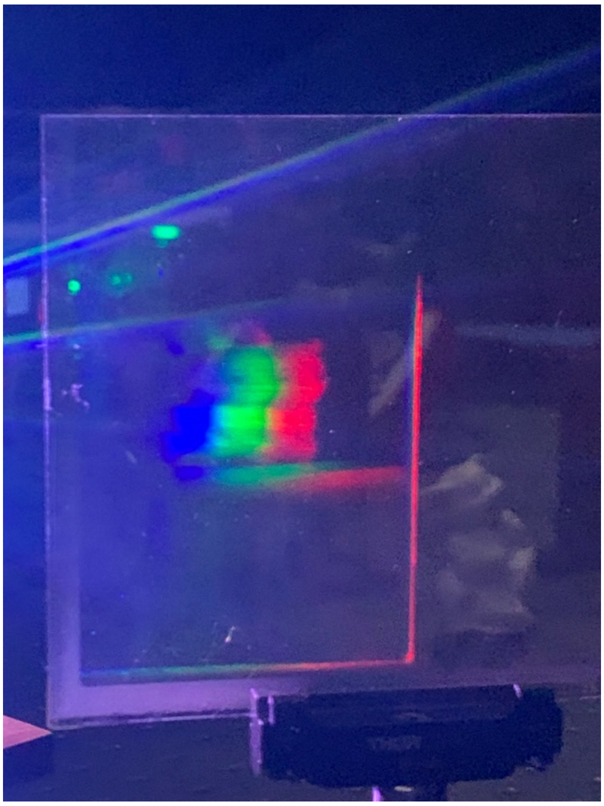

FIG. 4: Photo of the Transmission Hologram illuminated a by red, green and blue LED light.

The intensity of the light at the plate was measured to be 7 $\mu W$ and at the object 12 $\mu W$ during low exposure, thus total is 19 $\mu W$. (This is not what it is meant to be as the ratio was meant to be 4:1) The intensity at exposure was 108 times this intensity thus the intensity taken for exposure time calculations is;

$$P_{exp} = (108)(0.019) = 2.052\ mJ\ s^{-1}. \tag{15}$$

The given aperture size for the photo diode was $d_{app} = 0.95\ cm$ thus the power density per $cm^2$ is calculated by;

$$p_{exp} = \frac{2.052}{\frac{\pi(0.95)^2}{4}} = 2.895\ mJ\ s^{-1}\ cm^{-2}. \tag{16}$$

The exposure energy for the plate under green (532 nm) light is 30 $mJ\ cm^{-2}$. Thus the theoretical exposure time is;

$$t_{exp} = \frac{30}{2.895} = 10.36\ s\ \approx 10\ s. \tag{17}$$

As the light is split, the instructions state to double the total exposure time. This is doubled again as to ensure the age of plates have no effect on the hologram thus the final exposure time is;

$$t_{exp} \approx 40\ s. \tag{18}$$

*The light intensity was not found for this setup and thus the calculations above use the light intensity values for experiment 3. Although, the exposure time was accidently done perfectly at* $t = 40\ s$.

The resulting hologram (FIG. 3) was visible and clear and could be seen only under the low-intensity coherent exposure light and a coherent LED light. The hologram was placed under 3 coherent LED lights of differing wavelengths and the affect wavelength on the transmission hologram was observed (FIG. 4).

1. **How are the fringe recordings differ between this transmission hologram and reflection hologram recorded in the previous experiment.**

The fringes in the reflection hologram are produced parallel to the film surface. The fringes produced in the transmission hologram are perpendicular to the film surface and is the main controlling factor for whether the hologram can be observed in incoherent light.

2. **Why can a transmission hologram not be observed using white light illumination?**

As observed in FIG. 4, the wavelength of light changes the position and size of the read hologram dependent on the wavelength of light. In a white-light illumination, the spectrum of light would blur the image completely and the hologram would not be able to be observed. This can be seen in the reliance on wavelength of the mathematical representation of the reconstructed field;

$$\beta' B A^* a(x, y) \exp\left(i 2\pi y \frac{\sin 2\theta}{\lambda}\right). \tag{9}$$

A more physical interpretation is that as the reference and object beams are not parallel or perpendicular, dispersion is allowed to occur to a much higher degree. Whereas for the reflection holograms in experiment 1 and 4, the reference and object beams are anti-parallel and perpendicular respectively, not allowing significant dispersion to occur.

3. **Explain the difference between a phase and amplitude hologram? Which is relevant to your experiments.**

A phase hologram encodes the interference pattern of the incident and reflected light in turn encoding the phase of the field present as positionally dependent refractive indexes (acting as diffraction gratings). This allows the viewer to observe the reconstructed image accurately from a range of angles, creating the 3D affect. An amplitude hologram only encodes the magnitude of the intensity of the light passing through the recording media and thus the reconstructed image can only be viewed from a single angle accurately, the angle at which the object was relative to the recording media.

For this experiment, all the configurations were recording phase holograms.

4. **What are the coherence requirements of the light source for recording and reading the hologram.**

As explained previously, the coherence requirements for reading the hologram are strictly coherent light. For recording the hologram, the Temporal coherence alike to the reflection hologram are strict but more importantly for a transmission hologram is Spatial coherence. Spatial coherence is the degree to which the light waves emitted from a source maintain a constant phase relationship across the cross-section of the beam. A laser has great Temporal and Spatial coherence and thus is commonly used.

5. **Provide a physical interpretation of observed changes to the reconstructed image when the wavelength of the illumination is changed.**

For a differing wavelength, the reconstructed image changes in position (can be seen in FIG. 4). This is due to dispersion of the light where differing wavelengths diffract at different angles. A higher wavelength will be observed at a greater angle from the original image. Theoretically, with a differing wavelength, the size and clarity of the image will change but this was not observed clearly most likely due to the original clarity of the hologram.

6. **What physical parameters define the spatial resolution of the hologram.**

The spatial resolution of the hologram is the measure of how much detail the hologram can capture and reproduce. There are several physical parameters that influence spatial resolution including Wavelength of Light, Size of the Recording Medium, Distance between Object and Plate, Holographic Material Properties, Aperture Size, Precision of Optics, Angular Separation of Beams, Coherence Length of Light Source and Stability and Vibrations. The most relevant parameters to these experiments are the

a) Wavelength of light: Shorter wavelengths allow for finer details to be recorded and reconstructed thus theoretically in FIG. 4, the greatest resolution of the images should be that of the blue light and least that of the red.
b) Size of recording material: If the plate is larger, it can record more information about the field and thus the reconstructed image is produced to a greater resolution.
c) Distance between Object and Plate: If the object is closer to the plate during recording, the physical size of the reconstructed image will be bigger. This allows for finer detail to be captured in the hologram.

7. **Observe the effect of illuminating just a small section of the hologram. This can be done by illuminating through a mask with a small window or variable aperture. How would you interpret these observations?**

This was not completed but from research, the image can be partially reconstructed and information of the depth of the image can be lost or altered. The reconstruction of the image comes from all parts of the plate and thus partially covering a section can reduce the quality of the entire hologram. Intuition states that it should act like a shadow where if I cover a section, that section will be lost but, in this case, the whole hologram can be altered.

## Experiment 3: Double-exposure holographic interferometry

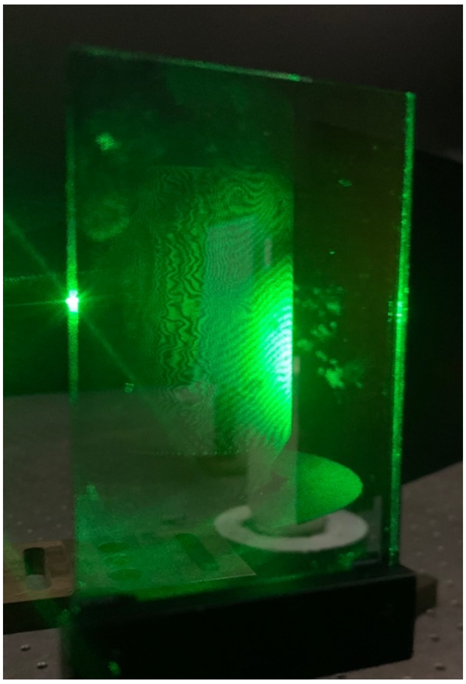

FIG. 5: Photo of the double-exposed Transmission Hologram illuminated by the low-intensity exposure light showing the holographic interferometry.

The calculations for the exposure time are identical to that of the previous experiment. As for this experiment there is a double exposure, the ratio of first to second exposure will be 25:75. As total exposure time was found to be $t_{exp} = 40\ s$ the first exposure was done at $t_1 = 10\ s$ and $t_2 = 30\ s$. The exposure of the second exposure is not important, but the first exposure needs to record enough of the field without completely exposing the film.

The holographic interferometry on the can was evident see as horizontal fringes across the body of the can in FIG 5. These fringes originate from the slight expansion of the can when the weight was taken off for the second exposure. This effectively changed the height of the can by a small amount. During the second exposure, the slight change in height caused the recorded interference pattern to shift slightly which constructively and destructively interferes with the original exposure. This is why there are observed fringes on the body of the can.

The physical interpretation of the fringes are a magnitude and direction of strain applied to the can from the weight. The fringes are not perfectly horizontal as the can cannot hold a constant shear strain across its cross section. This is why it is easier to crush a can from the side than axially. The fringes are relatively equally spaced, and this is due to the axial strain in the can being constant along the height of the can, but it still varies due to the weight force not being perfectly vertical and physical imperfections of the can.

(I'm not too sure about quantitative analysis but theoretically one could measure the peak-to-peak distance and calculate the axial strain from there.)

**Experiment 4: Reflection hologram**

FIG. 6: Photo of the Reflection Hologram illuminated by the low-intensity exposure light.

The intensity of the light at the plate was measured to be 11 $\mu W$ and at the object 13 $\mu W$ during low exposure, thus total is 24 $\mu W$. (This is not what it is meant to be as the ratio was meant to be 2:1) The intensity at exposure was 108 times this intensity thus the intensity taken for exposure time calculations is;

$$P_{exp} = (108)(0.024) = 2.592\ mJ\ s^{-1}. \tag{19}$$

The given aperture size for the photo diode was $d_{app} = 0.95\ cm$ thus the power density per $cm^2$ is calculated by;

$$p_{exp} = \frac{2.052}{\frac{\pi(0.95)^2}{4}} = 3.657\ mJ\ s^{-1}\ cm^{-2}. \tag{20}$$

The exposure energy for the plate under green (532 nm) light is 30 $mJ\ cm^{-2}$. Thus the theoretical exposure time is;

$$t_{exp} = \frac{30}{2.895} = 8.20\ s\ \approx 8\ s. \tag{21}$$

This is time is doubled as to ensure the age of plates have no effect on the hologram thus the final exposure time is;

$$t_{exp} \approx 16\ s. \tag{22}$$

The resulting hologram (FIG. 6) was visible and clear and could be seen under the low-intensity coherent exposure light and in non-coherent light from a lamp or sunlight. It has the same holographic properties as the hologram produced in experiment 1 but the object beam is separate from the reference beam. The beams are perpendicular to each other so dispersion affects are minimal, and such can be seen in incoherent light.

**Experiment 5: Michelson Interferometer**

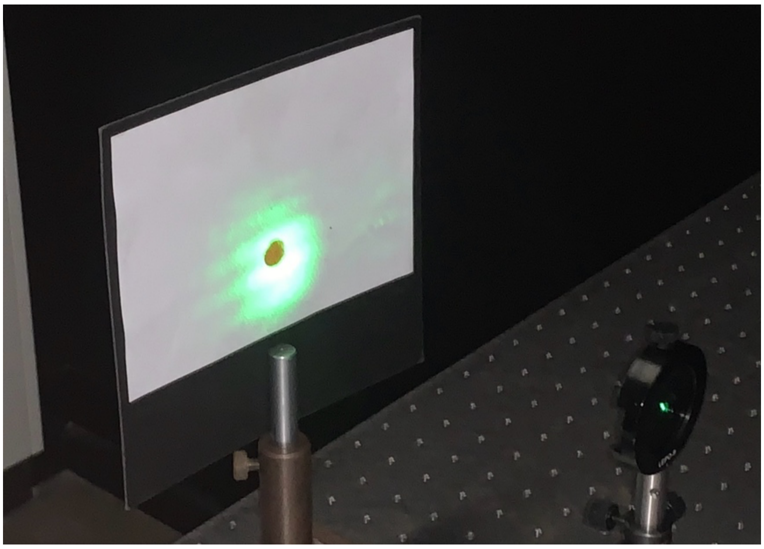

FIG. 7: Photo of the interference fringes from the Michelson Interferometer setup.

The interference fringes were very evident on the screen. By tapping the bench lightly, small vibrations were introduced into the system and the fringes would quickly disappear and turn into a homogonous circle. The fringes only reappeared just as the vibrations ceased. The system was extremely sensitive whereby disturbing the airflow of the incident beams the fringes would change but to a lesser degree than that of vibrating the system.

The system was too sensitive to try and change the distance of the mirrors, but the expected effect would be to see the fringes evolve as the phase difference in the beams would change.

(This was an absolute pain to try and setup, aligning all the beams to a single point on the beam splitter took most of the second lab.)

## CONCLUSION

This experiment was successful in exploring the formation and reconstruction of phase holograms. It showed the nature and difference between reflection and transmission holograms in their formation and reconstruction. Reflection holograms can be reconstructed in incoherent light due to its minimal dispersive effects while transmission holograms are extremely sensitive to the wavelength bandwidth of the light for reconstruction. This enforces the mathematical representations of both scenarios as the inclusion of a wavelength term in the transmission hologram reconstruction field creates the observed sensitivity to chromatic coherence. The double exposure holographic interferometry created a physical representation of strain in an object through interference fringes across its body and the Michelson Interferometer showed the interference pattern from a phase difference caused by differing path lengths.

## REFERENCES

[1] – Holography PHYS3114 Student Notes

[2] – Holography PHYS3114 Operating Instructions