# REAL TIME HOLOGRAPHY WITH POLYMER FILMS

Obinna Anyanwu, Kristin Beck, Craig Gorin, Michael Ireland, Matthias Jamison-Koenig,
Ryan Nolan, Rachel Ostrand, Ryan Perumpail, Prasad Tare, Eric Van Nostrand, Charles Won

Advisor: David McGee, Ph.D
Assistant: Katy Rolfe

## ABSTRACT

Holography has recently returned to the forefront of physics with new applications in security verification, display technology, and information storage. With the development of cost-efficient organic polymer films, holograms are developing into more than an amusing artistic media. Holograms store information about the intensity and phase of light reflected from an object, giving depth to the resultant image. Thus, information can be represented in three dimensions as opposed to two. Many such compact images can be placed on a film and subsequently recreated by changing the angle of the incident light and the position on the film to each image's location. This process is the key to using holography for mass data storage. In holographic reconstructive imaging the wave nature of light allows for the generation of a unique diffraction grating which may be used to store data. Although various companies have implemented this property in data storage technology, none have solved the problem of long term image decay.

In this project, the goal is to store holograms in an organic polymer film using an optical breadboard, a helium-neon laser, a beam splitter, mirrors, and kinematic optical mounts. This experiment is designed to measure the decay time for a hologram when placed in a split-beam image setup. The angular selectivity of the holographic process is also used to store multiple images on the same film. Image retention of the film is then measured using a digital camera along with image analysis software.

## INTRODUCTION

Holography is a technique, like photography, that is used to record an image of an object. When a picture is taken using conventional photography, the film is only able to record the intensity of the light received by the camera. As a result the information concerning the depth of the object is lost, and thus the image appears to be flat. On the other hand, holography is able to generate depth within a picture by storing it as an interference pattern within the film. When this film is illuminated by light of the same wavelength with which the image was recorded, the original pattern of waves that reflected off the object is recreated, giving the illusion of depth. The word holography itself is derived from the Greek words 'holos' and 'gramma,' which together mean 'whole message' [1].

## TECHNICAL BACKGROUND

Holography is based on the principles of interference and diffraction. Interference and diffraction are phenomena specific to waves, and light is no exception.

Interference is the addition or subtraction of the energy of two waves. It occurs any time two waves overlap in space. If the two waves are in phase, the resultant beam is double the amplitude of the original beams. This type of interference is called constructive interference, as illustrated in Fig. 1 (A). Waves that are in phase are synchronized and their crests occur at the same time. On the other hand, waves that are half a wavelength out of phase will completely cancel each other out. The resultant wave will have zero amplitude because the amplitudes of the original beams are equal in magnitude and opposite in sign. This type of interference is called destructive interference and is illustrated in Fig. 1 (B).

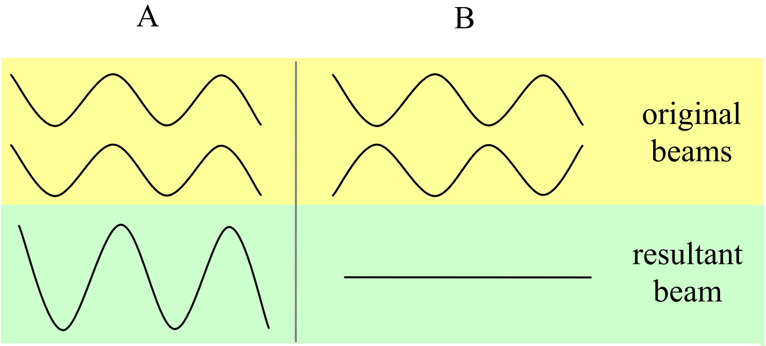


Fig. 1. An illustration of constructive (A) and destructive (B) interference

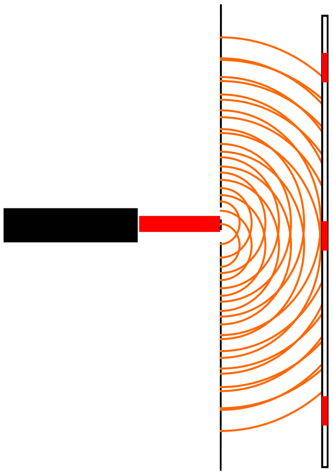
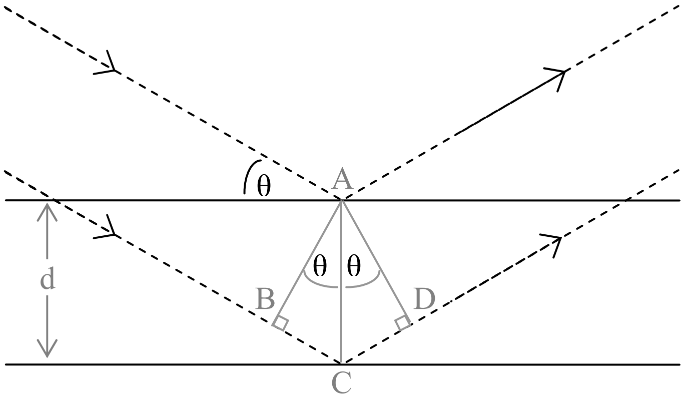


Fig. 2. Diffraction through 2 slits

Related to interference is diffraction, which involves the bending of light by sending it through a small opening. When this phenomenon occurs, the light is spread out in all directions on a plane, creating an interference pattern. This pattern is a series of light and dark bands that represent constructive and destructive interference by the interfering light waves leaving the opening. These interference patterns can also be created by sending light through two slits (Fig. 2) or by using a diffraction grating, which is a collection of thousands of small slits. In holography, the interference pattern created by the interference of two waves is recorded onto the film, creating a diffraction grating within the film.

The Bragg Equation

In holography, diffraction gratings are created within the film in order to encode an image with depth. The Bragg equation, discovered by William Henry Bragg and William Lawrence Bragg in 1912, is used when describing the properties of diffraction gratings as they relate to light waves [2]. This equation gives the conditions for constructive interference (Fig. 3).



$$\Delta \text{Path Length} = BC + CD = 2d\sin\theta = n\lambda$$

Fig. 3. An illustration of the Bragg equation.

To derive this equation, picture two parallel partially silvered mirrors. Light will both pass through, and reflect from these surfaces. When a beam of light incident on the diffractive grating hits the material, some fraction of the light will pass through and reflect off the second plane. Examining only these two beam paths, the approximate condition for constructive interference can be determined. When the difference in path length between the two reflected waves is an integer multiple of the wavelength, the waves interfere constructively, forming a bright spot. Applying trigonometry to the situation shown in Fig. 3 yields the following equation for constructive interference:

$$2d\sin\theta = n\lambda,\ n = 1, 2, 3\ldots \tag{1}$$

This equation is commonly known as the Bragg equation. It has several uses in diffraction gratings. Using this equation, the properties of a specific grating or beam of light can be calculated. These properties include the width of the grating, the angle of incidence, and the wavelength of light.

The phenomena of interference and diffraction make it possible to record holograms. To begin the process, light is first reflected from an object onto holographic film. This reflected light meets with the reference laser beam within the film, which creates an interference pattern. The role of the film is to capture this pattern, creating a diffraction grating throughout the entire film, similar to the diffracting planes shown in Fig. 3. The properties of the film allow the interference pattern to be stored as a unique grating for a short period of time. In order to recreate the three-dimensional image (the hologram), it is necessary to illuminate the film with only the reference beam at an angle that satisfies the Bragg equation. By doing so, the light travels through and reflects from the grating, recreating the individual paths traveled by each ray of light, and reproducing the stored image.

In addition to the mathematical physics and the underlying theories, holography also requires the use of several specialized kinds of optical equipment, including beam splitters, mirrors, and lenses. There are two types of lenses that are of particular interest in this paper. The first is the diverging lens, which widens a beam of light in order to cover the object completely. The second lens of interest is the converging lens, which takes light and concentrates it into a smaller area. This lens is used when it is necessary to concentrate the image beam onto the film.

## BRIEF HISTORY

The basic concepts behind holograms were discovered years before technology provided the chance for their creation. In 1917 Albert Einstein predicted the creation of monochromatic light through stimulated emission, laying down the theory behind the laser. Dennis Gabor conceived the idea for the hologram in 1947, making the first holograms with white light sources through transparencies. In 1971, Gabor was awarded the Nobel Prize for his pioneering efforts in holography [3].

The first step towards making holograms and holographic research more accessible occurred in 1954, when Charles Townes invented the maser [3]. The maser was the pioneer in the field of coherent radiation, producing an intense beam of microwaves, creating the effect that Einstein had predicted 38 years earlier. Just six years later, Theodore Maiman helped to advance the field by creating a similar apparatus in the visual light spectrum [3]. The laser, as this device was called, and the maser both create coherent radiation by reflecting monochromatic light through a lasing medium consisting of atoms highly above ground state [4]. Lasers are now available in a broad range of wavelengths.

After the advent of the laser, holography gained a foothold in optics. In 1962, the "off-axis" technique for recording holograms was developed by Emmett Leith and Juris Upatnieks. This technique, in which the reference beam for the hologram is out of the normal viewing range, is the main technique used today. Other techniques, such as Yuri Denisyuk's white light reflection hologram and Steven Benton's white light transmission hologram, allow for the viewing of holograms under incoherent light sources, such as regular white light from an incandescent bulb. Movie holography was developed in the 1970s with a pulsed laser technique for storing multiple images at different viewing angles in the same film [5].

## TYPES OF HOLOGRAMS

There are several methods that can be utilized to create holograms. Reflection and transmission holograms are the types of holograms that are familiar to most people and can be seen on credit cards and in other decorative capacities, such as wrapping paper. Reflection holograms differ from transmission holograms in that they can be viewed through white light. With reflection holograms, it is not necessary for the viewer to stand opposite the light source, as the light reflects back towards him. The method used in our research is the transmission hologram, developed by Dennis Gabor in 1947. This method involves the use of monochromatic light to record the image onto the film. In order to play the image back, it is necessary to use the same wavelength of light. Here, the viewer stands on the opposite side of the beam to view the image. Transmission simply refers to the fact that the light must travel through the film before the image can be viewed. Either method can be used to create three-dimensional holograms [6].

## APPLICATIONS

The applications of holograms are varied and far-reaching. Currently, holography has uses in business, counterfeit protection, the military, and many other fields. Grocery store scanners use holograms to read the barcodes on items [7]. On credit cards, unique holograms are printed on each card to reduce incidences of credit card fraud [8]. The military also uses holography in heads-up-displays (HUD's) for pilots, allowing them to concentrate on flight [7]. The HUD projects a holographic image of the instruments on the dashboard onto the windshield so that the pilot does not need to look down as he flies at speeds exceeding that of sound. Current research into holography holds even more promising prospects. Future uses of holography are being explored in data storage, where it may be possible to store many times more information than conventional discs while having no moving parts [7].

## PHOTOREFRACTIVE FILMS

In order to create a specific diffraction grating for a transmission hologram (a hologram in which the reference beam passes through the film as opposed to reflecting off it), it is necessary to record the interference pattern in a suitable light sensitive medium.

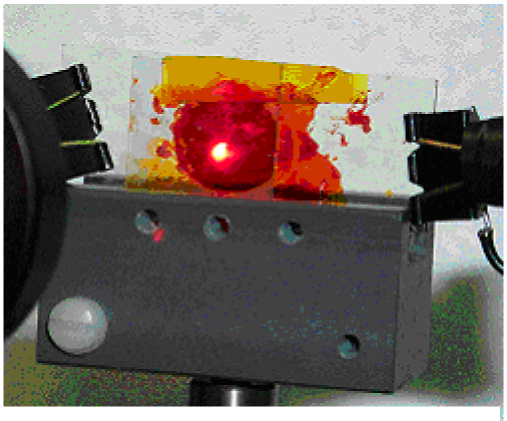


Fig. 4. The photorefractive film used in the experiments

Photorefractive films are one example of light sensitive films that can be used for holograms. Photorefractive films store holograms by changing their refractive index in areas of higher light intensity. Some inorganic crystals, such as lithium niobate and barium titanate, exhibit this effect. Small imperfections in the crystalline structure, a result of holes or contaminant atoms, cause an imbalance of charge in certain areas of the crystal. In areas where light is incident on the crystal, the charges are free to move. However, this mobility is hindered as light intensity decreases. After a period of exposure to an intensity pattern, a

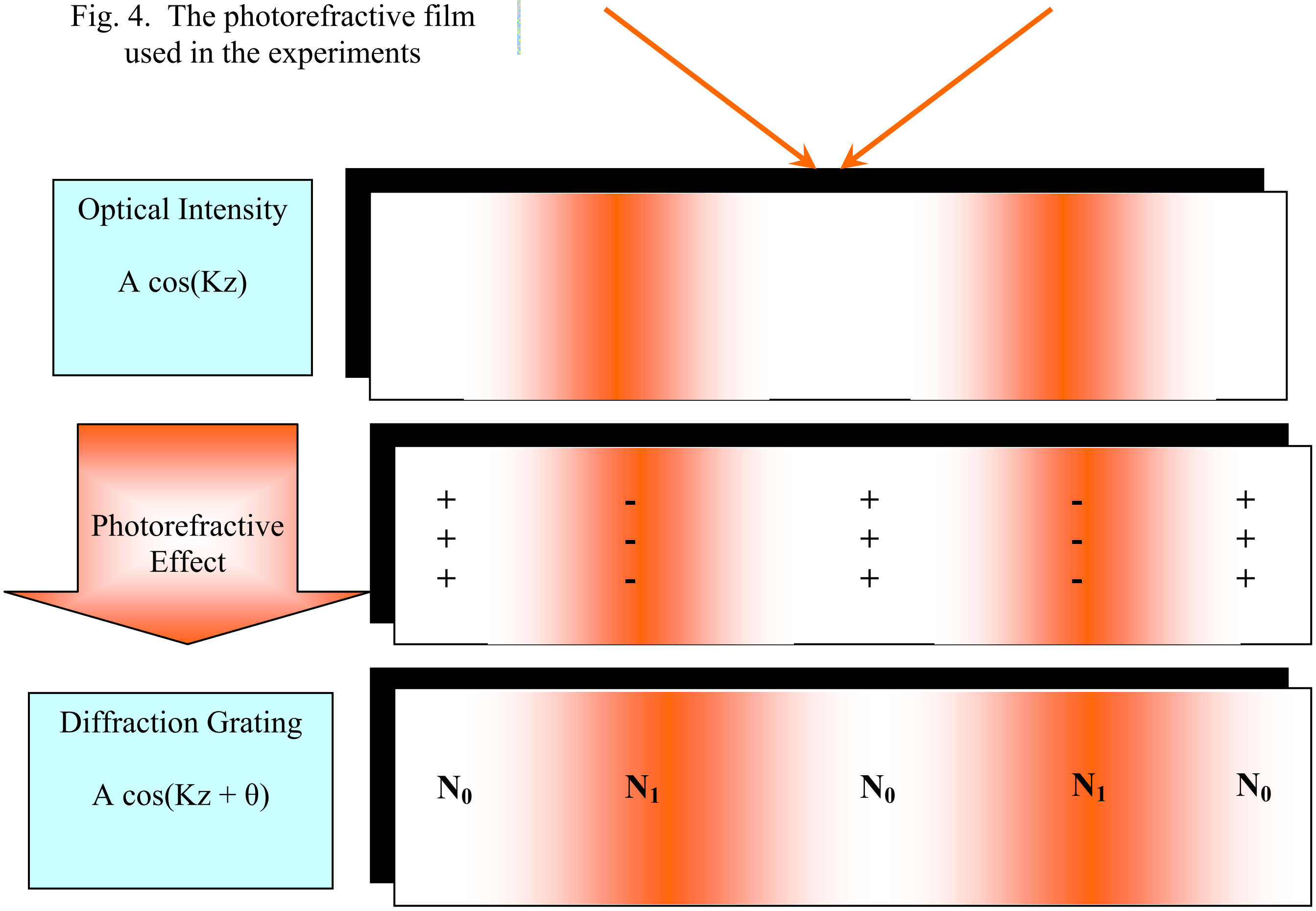


Fig. 5: The Photorefractive Effect

diffraction grating mimicking this pattern develops in the crystal as the electric field induced from the incident light distorts the crystal lattice, changing the refractive index of certain regions, as shown in Fig. 5. The exposure period is inversely proportional to the intensity of light incident on the film and the ease of charge movement in the material. In order to decrease exposure time, a more powerful laser source may be used or an external electric field can be applied across the film. The main caveat of inducing a separate electric field is that the field itself will change the diffraction grating formed because the charges are no longer randomly drifting uniformly throughout the material but are drifting in the direction of the imposed field. [9]

These crystals were the first commonly used photorefractive material in holography. However, the mid 1990s gave rise to a new variety of photorefractive medium for this application. These materials, known as photorefractive polymers, are not only easier to produce than photorefractive crystals, but also much cheaper to produce. Although they are relatively new, these polymers have been developed to the point that their performance is as good as, if not exceeding, that of traditional photorefractive crystals [10]. The polymers of the film form a charge conducting network in which dye molecules are blended. This experiment utilized one such photoconducting polymer (Fig. 6), a mixture of polymer PVK (poly(N-vinylcarbazole)) and sensitizer TNF (2,4,7-trinitro-9-fluorenone). The polymer acts in almost exactly the same manner as the inorganic crystals. When light is incident on the material and an external electrical field is applied, charges are free to move. Negative charges move away from the light areas, so a grating of charges is created. However, changes in the index of refraction are not apparent without the addition of the dye molecule. The internal electrical fields in the film orient and stretch this polar molecule (either DMNPAPhBuE or DMNPAPBE), which changes the index of refraction. ECZ, a plasticizer, is added to facilitate dye movement [11]. The films used in this project were fabricated at Drew University as part of a collaborative project between the Chemistry and Physics Departments.

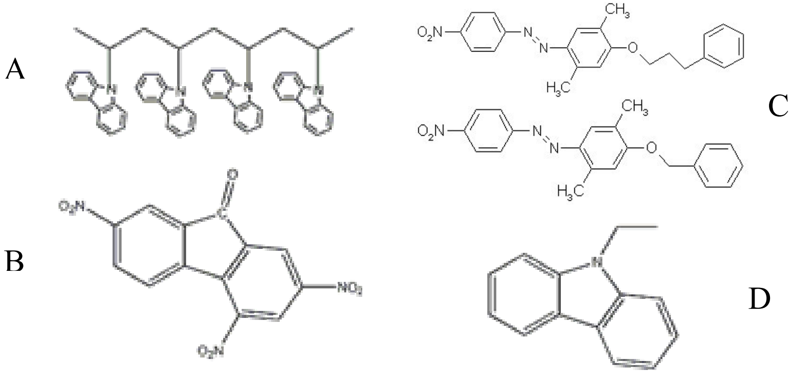


Fig. 6. PVK (A), TNF (B), dye molecules (C), and ECZ (D)

The deformations of the dye molecule allow for two different types of recording. When an external electrical field is induced, both orientation and “stretching” (referred to as the electro-optic effect) of the dye molecule can occur. Without the external field, the dye molecules exhibit only the electro-optic effect, which arises from a distortion of the electronic states of the dye. Hence orientation of the molecules cannot occur. Both of these techniques have been used successfully on a regular basis in the laboratory.

In many photorefractive materials, no chemical development is necessary, which results in quick and easy production of fairly good quality holograms. However, reading the hologram with a uniform reference beam simultaneously records over the diffraction pattern stored in the film.  This process occurs because a uniform reading beam will re-excite trapped charges from previously recorded holograms.  One goal of this project is to find the rate of decay of the hologram when viewed through the reference beam.

## EXPERIMENTAL SETUP

For this experiment a number of optical tools are necessary (Fig. 7).  The entire experiment was constructed by the student teams on a 2 x 4 foot optical breadboard.

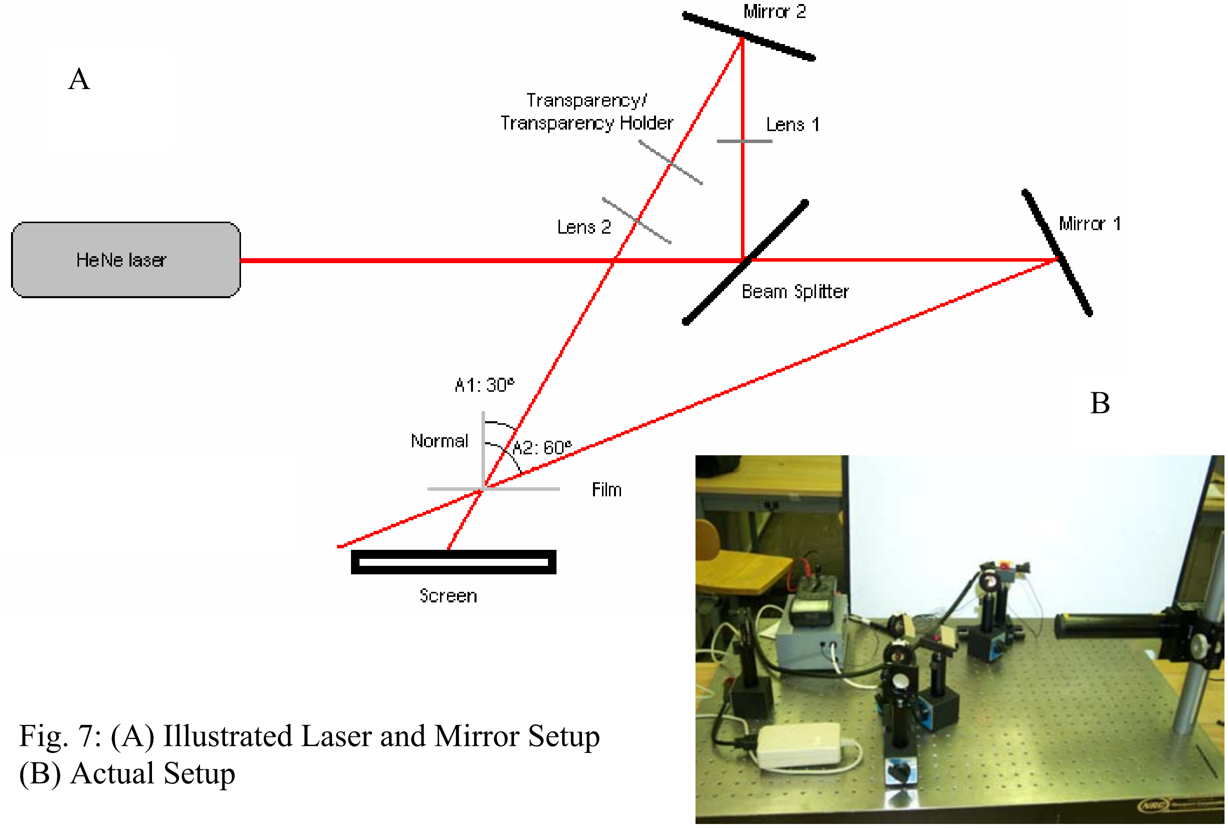


Fig. 7: (A) Illustrated Laser and Mirror Setup
(B) Actual Setup

The breadboard is designed to minimize vibrations and its steel top allows the placement of optical components by using magnetic mounts or by screwing components directly into regularly placed holes.  The light source is a helium-neon (HeNe) laser (Fig. 8), which is used to produce an intensely focused beam of light with a wavelength of 6328Å, which the human eye perceives as red.  When the beam leaves the laser, it must travel parallel to the optical bench on which the experiment is conducted.  To ensure that the beam is parallel, a clear metric ruler is used to measure the height of the beam once as it is emitted from the laser and a second time as it crosses a point across the work surface.  The angle of the laser is adjusted as necessary.  A beam splitter is positioned in the path of the laser, and is angled in such a way that half of the light continues through the device while half of the light travels directly perpendicular to the incident path. The half of the beam that bounces off Mirror 1 (the reference beam) reaches the film at 60º to the normal.  The half of the beam that is reflected from the beam splitter, referred to as the object beam, travels perpendicularly through a diverging lens of focal length -50 mm.  This process enlarges the beam so that when it reaches the object, it will be large enough to cover the object completely.  The enlarged object beam then reflects off of Mirror 2 and reaches the object to be recorded.  In this case, the object to be recorded is a picture printed on to a transparency.  After moving through the transparency, the beam reaches the second lens. This time, the lens is a converging lens with a focal length of 75 mm. The lens brings the beam back into focus on the film. The beam hits the film at a 30º angle to the normal of the film. It must intersect the reference beam exactly in the film.

Two butterfly clips attached to the film allow a high voltage to cross the film. Behind the film is a screen onto which the laser beams and, later, the final holographic image are projected. After the film is exposed, the object beam is blocked and only the reference beam shines through the film. The beam passes through the diffraction grating in the film and projects the hologram onto the screen.

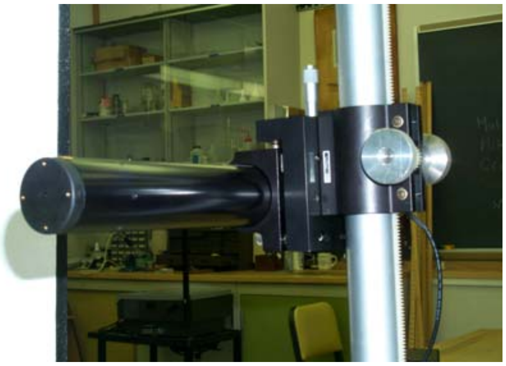


Fig. 8: Helium-Neon laser used for the experiments

Fine Tuning Alignments and Taking Data

The primary problem in an optical setup this sensitive is the proper alignment of beams. If the object and reference beams do not overlay exactly on the film, the image will not develop properly. There are several ways to align the beams precisely enough to create a crisp, clear image and to allow for accurate data. A rough alignment may be accomplished by manually sliding the magnetic holders along the table, and roughly adjusting the height. To fine-tune intersections on the plane perpendicular to the film, the fine adjustment knobs on the mirrors are used to change the angle slightly to achieve a focused intersection. To adjust focus even further, the film can also be moved in small amounts.

After aligning the beams, the lenses are placed into the setup, but these additional devices may change the horizontal and vertical alignment of the object beam. Therefore, further fine adjustment is often needed. When proper alignment is achieved, a diffraction pattern can be recorded on the film.

In order to develop an image more quickly, a voltage of about 6000V is applied across the film. When the voltage is applied and the laser beams are intersecting on the film, a hologram begins to form in the film. For the experiments in this paper, typical exposure times vary from 1-5 minutes.

After a hologram is formed in the film, the image is reconstructed when the reference beam diffracts through the holographic grating while the object beam is blocked. This image decays over time because the reference beam has a uniform intensity, which causes the dye molecules of the film to re-randomize their alignment gradually.

The camera is set up on a jack to give stability and an ideal viewing angle over a long exposure time (about 2.5 seconds). The original image is photographed, and then the projected image is photographed once every 15 seconds. A digital camera is used to record the image decay. These photographs are analyzed using ImageJ software.

### Multiple Holograms

Multiple holograms can be stored on the same film simultaneously. An image is projected onto the film and allowed to expose for a specified amount of time. The film is then rotated slightly (about 3 or 4 degrees) and another object is projected for a shorter amount of time. If the second exposure is too long, the first image may erase because the polar dye molecules within the film re-randomize. It is also possible at this point to store a third hologram with a shorter exposure time than the second object. Each separate object creates a unique diffraction pattern that can overlap with the other diffraction patterns because the angle of the beam entering the film differs enough to satisfy a separate set of Bragg equations. To reconstruct the stored images, the reference beam is focused on the film. As the film is rotated, a sequence of separate images is projected onto the screen.

An important thing to note here is the exposure times of the three different objects. Relative exposure times do not increase the image clarity or intensity. For example, exposing the film for 3 minutes, 1.5 minutes, and 1 minute produces no noticeable differences compared to 4.5 minutes, 2.25 minutes, and 1.5 minutes. However, it is most likely that changing the respective proportions of time allotted to each exposure will change the characteristics listed above. It is also critical not to overexpose the hologram because the film could burn out and yield no usable results.

This experiment has many opportunities for error. Human eyes are not as precise at aligning the beams as they need to be in order to obtain an ideal interference pattern. Timing is also crucial to the creation of a good hologram. An underexposed film will decay quickly and will not have a clear image. An overexposed film will not hold an image at all. In order to explore some of the many variables affecting the quality of stored holograms, the student groups built two separate holographic work stations and worked in rotating teams.

## DATA ANALYSIS

The holographic images produced are analyzed by the Java-based image analysis software ImageJ, which is distributed by the National Institute of Health. The program is capable of assigning values to each pixel of an image based upon the intensity or brightness of the pixel. Since the image size remains constant for each data set, and the camera is kept still during photography, it follows that an average change in the brightness values for all the pixels of an image can indicate an overall change in brightness for the image. Consequently, a decrease in brightness would represent the fading of the image, or holographic decay.

Therefore, for each image in each data set, ImageJ is used to calculate the mean brightness value of all the pixels of a hologram in a single instant. The experimenters assigned this

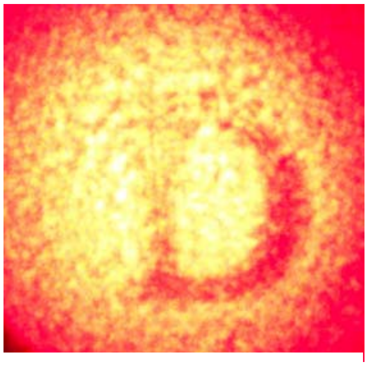


Fig. 9 ‘D’ Hologram

brightness value a unit of McGees in honor of the holographic team's project advisor. The McGee brightness values for each image are shown in the data tables that follow. Using the spreadsheet software application Graphical Analysis, curve fits were calculated for the data sets. An exponential decay curve fits the data very well. For the holographic "D" image (Fig. 9), the data was found to have a root-mean-square error of 0.053, which is much lower than the other error values offered by different regression fits (Fig. 10). For the holographic "Russia" image, an exponential decay curve is also very successful despite the lack of a catalytic electric field (Fig. 11). Therefore, it can be said with a degree of confidence that holograms decay exponentially, and equations such as the following may be used to find the McGee brightness of a hologram at a given amount of time. Tables 1 and 2 give the exact values of the data gathered.

The "D" and "Russia" hologram graphs indicating brightness versus time can be found below. Both images are stored as holograms on polymer-dye film with the "D" image recorded with the aid of an applied electric field while the "Russia" image was recorded without this aid. After exposure, the object is removed and only the reference beam illuminates the film. Photographs are then used to quantify decay.

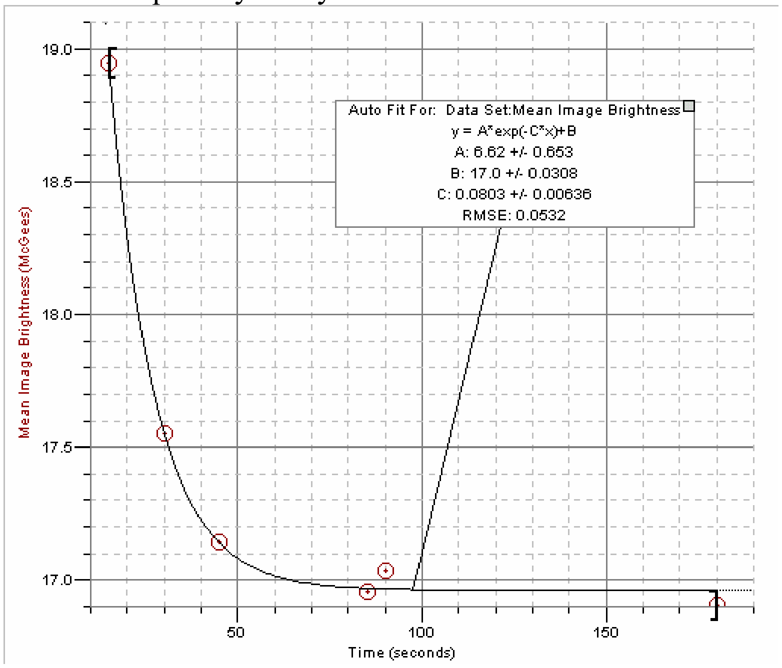


Fig. 10 'D' Hologram Graph. Brightness vs. Time
(Applied Voltage = 6000 V)

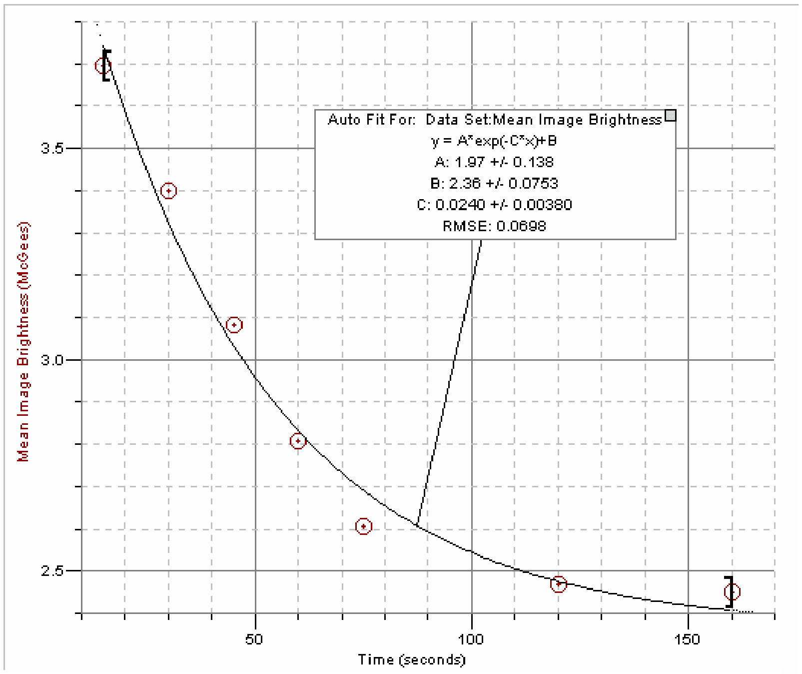


Fig. 11 'Russia' Hologram Graph. Brightness vs. Time
(No Applied Voltage)

Table 1: Brightness of the "D" holograms

| *t (time in seconds)* | *B (Brightness in McGees)* |
|---|---|
| 15 | 18.95 |
| 30 | 17.55 |
| 45 | 17.15 |
| 85 | 16.96 |
| 180 | 16.90 |

Exponential Regression: $B = 6.62e^{-.0803t} + 17.0$; RMSE of .0506

Table 2: Brightness of the "Russia" holograms

| *t (time in seconds)* | *B (Brightness in McGees)* |
|---|---|
| 15 | 3.70 |
| 30 | 3.40 |
| 45 | 3.08 |
| 60 | 2.81 |
| 75 | 2.61 |
| 120 | 2.47 |
| 160 | 2.45 |

Exponential Regression: $B = 1.97e^{-0.024t} + 2.36$; RMSE of .0698

Brightness Factor – McGee

The McGee is a relative value strongly dependent on the composition of the initial hologram, the light fluctuations in the room during photography, and the color of the surrounding objects in the photograph. As long as these objects and other variables are kept relatively constant from picture to picture, as they were in this experiment, the McGee is an effective tool for measuring change in brightness by comparing McGee values in consecutive pictures. However, because of the aforementioned factors, a lone McGee value for a given image is virtually meaningless. Because of the unit's variability, the change in McGees for one decaying hologram can have a much greater range than in another series of images. However, this variability does not affect the results because the coefficients of *t* in the regression equations compensate for these variables.

## CONCLUSION

In only four weeks, the team learned the basic physics behind interference, diffraction, lasers, and holography. The team constructed an experiment to record and read holograms using a novel polymer film and characterized image decay using digital photography. The data shows exponential decay for both images stored with and without an electric field across the film.

If there were more time, the groups could investigate a wider variety of phenomena. The team was surprised to observe that the decay rates were similar in both recording methods. Experiments could be performed to determine the relationship between these decay rates. In addition, it would be interesting to determine the differences in decay rate between the different dye molecules. Storing multiple images in one film was also accomplished by rotating the film between exposures. Future work would investigate the minimum angle between holograms and finding the best exposure proportions. Finally, further research could have allowed experimentation with the practical applications of holography, such as data storage, using the PVK:TNF film.

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## REFERENCES

[1] "Holography." 29 July 2004 <http://www.holophile.com/about.htm>
[2] Lonsdale, Kathleen. "Sir Lawrence Bragg." Britannica. 3 Aug 2004 <http://www.britannica.com/nobel/micro/83_18.html>
[3] "Laser History." Nobel e-Museum. 3 Aug 2004 <http://www.nobel.se/physics/educational/laser/facts/history.html>

[4] Weschler, Matthew. "How Lasers Work." Howstuffworks. 19 July 2004 <http://science.howstuffworks.com/laser.htm>

[5] "History of Holography." 2 Aug 2004 <http://www.holography.ru/histeng.htm>

[6] "5 Different Types of Holograms." 5 Aug 2004 <http://www.holo.com/holo/book/book5.html>

[7] "Technical Applications of Holography." 7 Aug 2004 <http://silver.neep.wisc.edu/~lakes/hoAppl.html>

[8] "Credit Card Fraud is on the Rise." AARP. 7 Aug 2004 <http://www.aarp.org/money/creditanddebt/Articles/a2002-10-01-FraudsCreditCards.html>

[9] Pepper, David, Jack Fienberg and Nicolai Kukhtarev. "The Photorefractive Effect." Scientific American. October 1990: 62-74.

[10] Peyghambarian, Nasser, and Bernard Kippelen. "Photorefractive Polymers: New Materials for the Information Age." Naval Research Reviews. 1997: 40-48.

[11] McGee, David, and Mark Matlin. "Photorefractive polymers: Materials science, thin-film fabrication, and experiments in volume holography. "American Journal of Physics. October 2001. 69.10: 1055-1063.

[12] Kallard, T. Exploring Laser Light. Maryland: American Association of Physics Teachers, 1977.

[13] Smith, Howard M. Principles of Holography. New York: Wiley-Interscience, 1969.

[14] McNair, Don. How to Make Holograms. Pennsylvania: Tab Books Inc., 1983.

[15] Rhody, Alan, and Franz Ross. Holography MarketPlace. California: Ross Books, 1997.

[16] Saxby, Graham. Manual of Practical Holography. Oxford: Reed International Books, 1991.