Student Name ______________________________ Date ____________________

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Department of Electrical Engineering and Computer Science

6.161 Modern Optics Project Laboratory

Laboratory Exercise No. 5 **Fall 2015**

Holography: An Application of Diffraction and Interference

The Pre-Lab Exercises must be completed BEFORE entering the Lab. In your lab notebook record data, explain phenomena you observe, and answer the questions asked. Remember to answer all questions in your lab notebook in a neat and orderly fashion. No data are to be taken on these laboratory sheets. Tables provided herein are simply examples of how to record data into your laboratory notebooks. Expect the in-lab portion of this exercise to take about 3 hours. **Please note that a formal written report is required for this Laboratory Exercise.**

PRE-LAB EXERCISES

PL 5.1 – Get Prepared to Start the Laboratory Exercises

Read the **entire** laboratory handout, and be prepared to answer questions before, during and after the lab session. Determine all the equations and constants that may be needed in order to perform all the laboratory exercises. **Write** them all down in your laboratory notebook before entering the Lab. This will ensure that you take all necessary data while in the Lab in order to complete the lab write-up. This preparatory work will also count toward your Lab Exercise grade.

PL 5.2 Preparation for Making Holograms

In Lab Exercise 5.2, your group will be making one type of hologram. You will have the option of making: (a) a Denisyuk single-beam white-light reflection hologram (simplest), (b) a two-beam or multiple beam reflection hologram, (c) a two-beam transmission hologram (must be viewed with a laser) or (d) a rainbow hologram (pseudo-color – but it takes quite a while to setup and develop). For those with little or no experience with optics or holography, this is a great opportunity to get your feet wet (pun intended).

For this section of the Pre-Lab it is your job to find out more about these types of holograms - everything about exposure of the holographic film, its development, and processing will be explained on lab day However, before coming to the Lab you are advised to do some outside research on how to configure the holographic recording and readout setups for each of the four types of holograms listed above.

After you have decided which hologram you want to make, make a detailed sketch of the recording system you will use. – This includes placement of the object, lenses, laser, mirrors, beam splitters, holographic plate, and any other items you might need (e.g., slits, wave plates, irises, etc…).

Here are some useful tips to consider before coming to the MOL to make holograms:

(1) You should bring some *interesting* objects from which we can make holograms. Such objects should not be dark in color, nor should they exceed a volume of 3”x3”x3”.

(2) Those students whose objects we use will be able to take home a copy of their hologram. Otherwise, holograms made in the MOL will be archived for demonstration to future students. You will need your own laser to view the transmission holograms at home. Reflection holograms will be viewable in white light.

(3) Make sure to wear clothes that can handle stains. Also, you will not be able to leave to go to the bathroom while the plates are developing, so be sure to go beforehand.

(4) Be aware that it will be extremely dark at times in the laboratory, and that it can be fairly time-consuming depending on the complexity of the hologram you choose to make.

"‘By-the bye, what became of the baby?’ said the Cat. ‘I’d nearly forgotten to ask.’ ‘It turned into a pig,’ Alice answered.”

– Lewis Carroll, *Alice in Wonderland*

IN-LAB EXERCISES

In the first holography lab session you will observe several holograms and participate in making one (or more) simple holograms. In the second session, you will have the opportunity to design and make a more difficult type of hologram. Some options are listed below. Your report (not more than 4 pages) for this section of the laboratory exercise will be graded by both the writing and laboratory staff. For this assignment assume your audience is a fellow 6.161 student. The Writing Coordinator will be looking at your grammar, at your sentence construction, for critical thinking on your part, and to see how clearly you can express your ideas in writing.

5.1 Viewing of Transmission, Reflection, White-Light and Computer-Generated Holograms

A collimated laser beam and a white-light source have been set up for viewing of four types of holograms.

(a) Illuminate the given laser-made **transmission holograms** with the divergent laser beam (remove the large collimating lens). For each hologram, find the direction of propagation of the virtual image, and view it directly (i.e., no lens or screen is to be used to view this image). Move your head around and tilt the hologram to get the best view of the image.

For the **hologram of the clock or the hologram of the train**, draw a diagram of the setup that gives a virtual image with the best fidelity. In your diagram, show the location of the virtual image and any other beams that exit the hologram. Use this information to infer the geometry of the setup that was used to record the hologram (reverse engineering).

(b) Illuminate the **reflection hologram of the coins** with the divergent laser beam and view the image through the hologram in reflection. Is the image you see real or virtual? Draw a diagram of the setup showing the location of the image and any other beams that exit the hologram. Use this information to infer the geometry of the setup used to record the hologram.

(c) Illuminate the **white-light hologram of the owl** with white-light from the overhead lights in the Laboratory such that the light strikes the hologram and then reflects an image into your eye. Tip the hologram from side to side and up and down. Draw a diagram of your readout configuration showing the location of the image or images. Describe your observations from tipping the hologram in the beam. Re-illuminate the white light hologram with the divergent He-Ne laser beam. What differences do you observe? Explain these differences. Use your observations to infer the geometry of the setup used to record this hologram.

(c) Put the collimating lens back into the system so as to generate a collimated laser beam. Illuminate the **first computer-generated transmission hologram** (written on a 4”x5” plate) with the collimated laser beam, and view the real image (it will spell a familiar acronym) on a distant screen. Draw a diagram of the setup showing the location of the real image and any other beams that exit the hologram. Use this information to infer the geometry of the setup used to record the hologram.

(d) Place the **second computer-generated hologram** (written on 2”x2” film) into the collimated laser beam. Now relocate the screen close to second computer-generated hologram. Move the screen away from the hologram slowly. What do you observe on the screen? How do you explain what you see on the screen with respect to what you see on the actual hologram? Ask the TA or LA to show you how this hologram was made.

5. 2 Real-Time Holography in Photorefractive Crystals

Objective
The goal of these experiments is to investigate real-time holographic information recording, storage, and readout in two different photorefractive recording media: a barium titanate ($BaTiO_3$) crystal and a bismuth silicon oxide ($Bi_{12}SiO_{20}$) crystal. The experiments are, for the most part, qualitative in nature. A full interpretation of the observations will require familiarity with charge transport in semiconductors, and the tensorial properties of the electro-optic effect.

The Crystals
Three crystals are provided: A, B (both barium titanate, $BaTiO_3$) and C, a bismuth silicon oxide crystal ($Bi_{12}SiO_{20}$). Crystal A has a roughly square cross-section and all six sides are polished. Crystal A is to be used for the experiment 5.2.8. Crystal B has a rectangular cross-section and only two sides are polished. Crystal B is to be used for experiments 5.2.1 to 5.2.7.

5.2.1 Hologram Recording, Storage, Readout and Erasure in $BaTiO_3$

In this experiment, a green argon laser beam (λ = 514 nm) is split into two portions and then the two beams are recombined in the $BaTiO_3$ crystal so as to write a phase grating (the blue line of the argon laser at 488 nm could also be used, but it is less efficient than the green line for this experiment). A half-angle θ of about 10° degrees between the two beams is typical. The grating is read out at the Bragg angle with a weak He-Ne laser beam (λ = 633 nm) and the diffracted beam intensity is recorded with the aid of a photodetector. The setup is as shown in Figure 1.

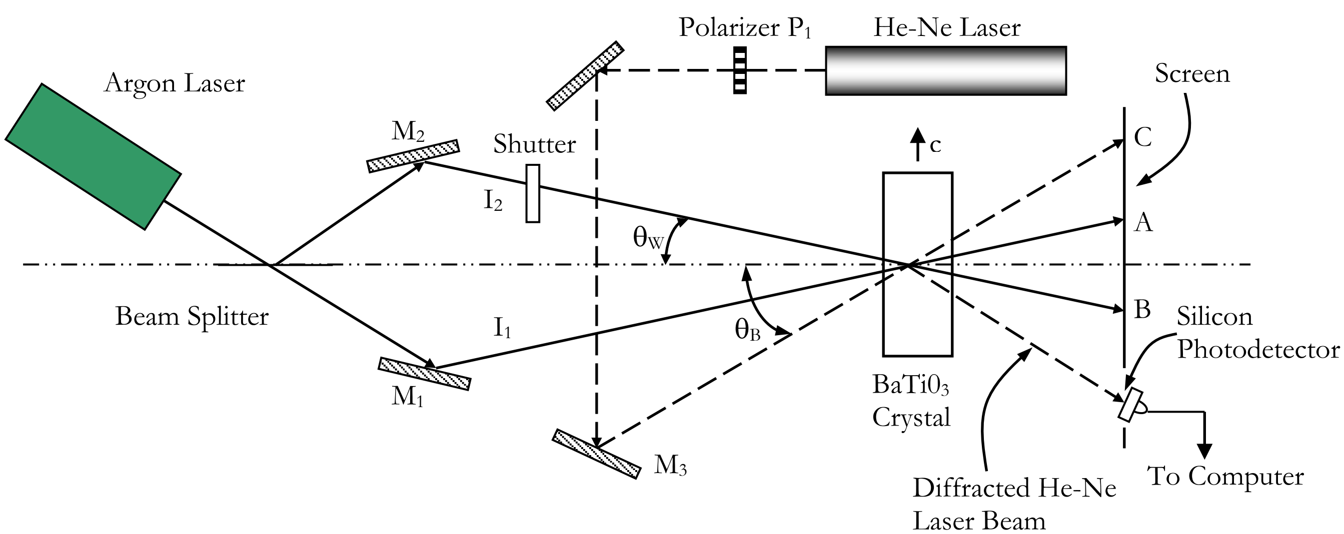


Figure 1. Set-up for measuring the diffraction efficiency of a $BaTiO_3$ crystal.

You should find the system already set up with the c-axis of the crystal in the plane of incidence of the argon laser beams as shown above. The angle of incidence of the He-Ne laser beam has been preadjusted so that the Bragg condition is satisfied. A fiber-optic coupled detector placed in the path of the diffracted He-Ne beam in conjunction with the BNC 210 National Instruments connector block and the computer is used to monitor the diffracted beam (alternatively, one could use a large-area photodetector and mask off the active area with a piece of black tape or cardboard to leave only a small opening roughly the size of the diffracted beam). The polarizer P_1 in front of the unpolarized He-Ne laser serves to alter the polarization of the red He-Ne readout laser beam incident on the crystal.

Rotate the polarizer so that the He-Ne laser light is polarized in the plane of incidence. Place the screen in front of the photodetector, so that the transmitted Argon laser beams, as well as the transmitted and diffracted He-Ne Laser beam can be seen on the screen.

To make sure that the system is functioning properly, first erase the grating in the crystal. This is accomplished by blocking one of the arms of the argon-laser-beam-writing system using the electronic shutter so that the crystal is flooded uniformly with the light from the second arm for about 60 seconds. The intensity of the diffracted He-Ne Laser beam on the screen should slowly disappear. Now open the shutter so as to record a phase grating in the crystal. The diffracted intensity on the screen should rise quickly to its saturation level.

5.2.2 Bragg Readout

(1) With respect to the $BaTiO_3$ crystal, is the He-Ne laser beam an ordinary beam or an extraordinary beam?

(2) Measure the polarization of the Argon laser beam. Is it ordinary or extraordinary polarized?

(3) By measuring the actual separation between the transmitted Ar laser beams on the screen, determine the angle between the two writing beams. (Do not touch the crystal when making these measurements).

(4) Calculate the period of the sinusoidal refractive index modulation that exists in the crystal using the results of part (3).

(5) Calculate the Bragg angle for He-Ne laser readout from your result in part (4). Compare this result with the measured Bragg angle, and explain any discrepancy between the two results.

(6) To experimentally find the Bragg angle, θ_B, we first calculated it to get an approximate value. Then an incremental search was performed about the calculated value (by changing the angle of incidence of the He-Ne laser beam on the crystal) until the maximum diffracted He-Ne beam intensity was obtained. Ask the TA or LA to demonstrate how extremely strict the conditions are for Bragg matching.

	T.A. or L.A. Signature

5.2.3 Diffraction Efficiency

(a) Remove the screen and use the Newport digital power meter and associated detector to measure the intensity of the He-Ne laser beam. With P_1 adjusted so that the readout light (He-Ne laser) is polarized within the plane of incidence (which contains the c-axis of the crystal) open the shutter and observe the buildup of the diffracted light on the photodetector. It is very important that you not bump or otherwise disturb the setup while a grating is being written into the crystal.

Write down the saturation intensity level of the He-Ne diffracted beam. Now place the Newport power meter in the readout He-Ne beam (before it enters the crystal) and measure the full intensity of the beam. Calculate the diffraction efficiency (power in the diffracted beam divided by power in the incident beam) of the crystal under these illumination conditions.

(b) Record the relative intensity of the argon laser beam using the Newport digital power meter.

(c) Now replace the photodetector in the path of the diffracted beam and connect the photodetector output to the computer. Use software provided to record the data on the digital chart-recorder (in LabView). Erase the crystal, then open the shutter and record the build-up of the diffracted light as a function of time on the digital chart recorder. Paste your data, or a reduced version thereof, into your report. Record the time scale on your plot, and calibrate the vertical axis using the saturation diffraction efficiency level of Part (a) as a benchmark. Identify the 10-to-90 percent rise time and the peak value of the diffracted He-Ne laser light intensity. Record these values on your plot.

5.2.4 Erase Time

With the same configuration as in 5.2.3, write the grating until the diffraction efficiency saturates. Now, close the shutter so as to block the light in one of the arms of the writing beam, and let the other argon laser beam, I_2 , readout the crystal. Record the decay of the grating by monitoring the diffracted argon laser beam intensity on the digital chart recorder as I_2 erases the grating while reading it out. Place your data, or a reduced version thereof, into your report. What is the 90-to-10 percent erase time?

5.2.5 Storage Time

With the same configuration as in 5.2.3, write the grating until the diffraction efficiency saturates. Now block the argon laser beam just after it exits the argon laser so that no write light reaches the crystal. Note the storage time of the grating, by setting the chart recorder for a 7-minute sweep and record the decay of the grating (as read out by the He-Ne laser) over the 7-minute period. Paste your data into your report. From your data, estimate the storage time of the crystal under these particular readout conditions.

5.2.6 Intensity Dependence of Write and Erase Times

Repeat the experiments in 5.2.3 and 5.2.5 with the argon laser beam at 3/4 of its original power. The laser power-control knob is on the back of the laser. Get the TA's help in adjusting the power of the laser beam. Paste your data into your report. Using your data, comment on the dependence of the diffraction efficiency, write time and the erase time on the pump power (argon laser power).

5.2.7 Dependence of Diffraction Efficiency on the Polarization of the Readout Beam

Repeat experiment 5.2.3 once more with the readout He-Ne laser light polarized perpendicular to the plane of incidence. Notice that the results are different from the original experiment with the He-Ne laser polarized in the plane of incidence. The point here is that it is possible to create a refractive-index grating (phase grating) that cannot be "seen" by readout beams of the "wrong" polarization. This happens frequently in anisotropic dielectric media where Δn is a function of the polarization of the light reading out the crystal.

5.2.8 Self-Pumped Wavefront Phase Conjugation (optional)

Barium titanate is unusual among photorefractive crystals in that it exhibits the phenomenon of self-pumped phase conjugation. That is, a single laser beam (example a diverging beam) entering a barium titanate crystal at the appropriate angle is retroreflected out of the crystal and back along its original path with the same wavefront shape as the incident beam (see Figure 2). Thus, the crystal acts as a phase-conjugate mirror.

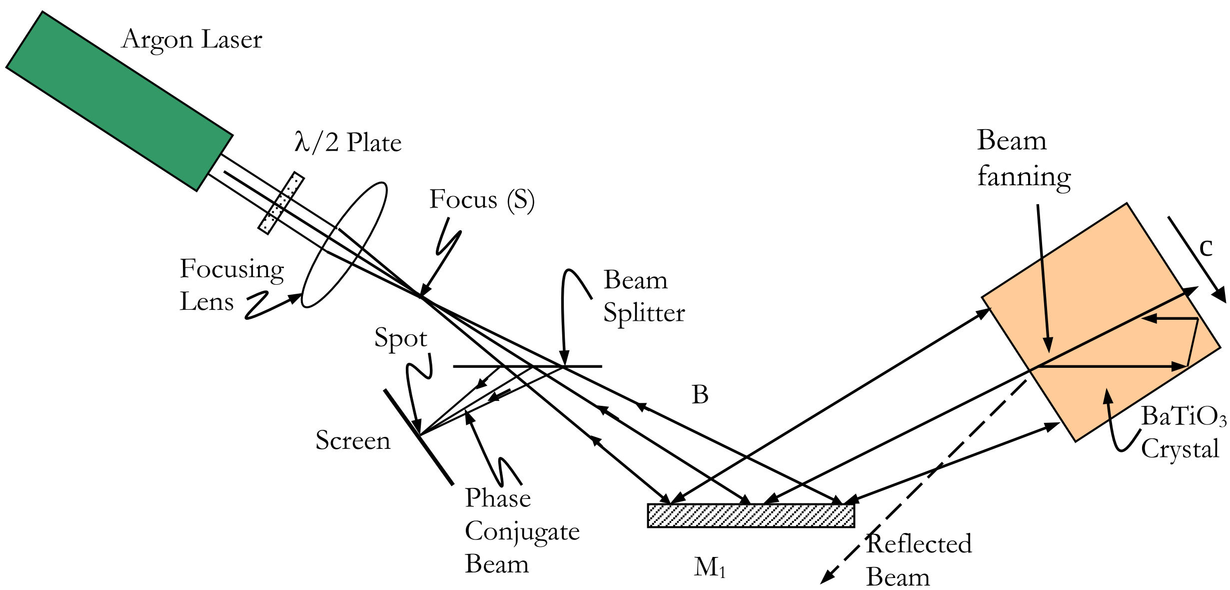


Figure 2. Illustrating the arrangement used to demonstrate self-pumped phase conjugation.

Beam fanning and two-beam coupling are essential to the mechanism involved in the self-pumped phase-conjugate process. These effects are stronger in $BaTiO_3$ for extraordinary polarized light (polarization along the c axis) than for ordinary polarized light.

To explore the phase conjugate property of the barium titanate crystal, we will make the following changes to the setup of Figure 1.

- Use crystal A. Place the crystal on the stand so that the chip on the long edge is at the bottom, the chipped corners are on the back, and the reflected beams from the front face of the crystal make an angle of about 30° with the incoming beam.

- Change the wavelength of the argon laser light to the blue line at 488 nm (TA will do this), and

- Modify the set-up of Figure 1 to that of Figure 2 without the lens. This is accomplished by closing the shutter in Figure 1 so as to get a single beam, and using the given halfwave plate to rotate the polarization of the argon laser beam into the plane of incidence (which contains the c-axis of the crystal). The key feature of this setup is a single extraordinary polarized writing beam interacting with the crystal.

(a) With the approximately-collimated laser beam entering one of the square faces of the crystal, rotate and translate the crystal as necessary until the phase-conjugate beam appears on the screen. You will have to wait about two to three minutes before the phase-conjugate beam is visible. Beam fanning within the crystal (see Figure 2) should be visible as the phase-conjugate beam builds up. Note that the phase-conjugate beam is approximately collimated even one meter away.

Convince the TA or LA that you have observed the phase conjugate beam.

	T.A. or L.A. Signature

(b) A second optional demonstration involves placing a weakly focusing lens (one that does not significantly overfill the crystal) in the argon laser beam as shown in Figure 2. The focused spot S before the beam splitter serves as the input-object for this demonstration. The phase-conjugate beam should appear as a focused spot of light at the same distance from the beam splitter as S is in front the beam splitter. Move the screen about one meter away from the setup and note that the phase-conjugate beam is divergent, as expected.

(c) A third optional experiment involves removing the lens from the system, and placing the given aberrator in region B of the beam path. Describe and explain your observations.

(d) Remove the aberrator after steady state has been reached. Describe and explain the response due to the removal of the aberrator.

5.2.9 Photorefraction in $Bi_{12}SiO_{20}$ (optional)

Bismuth Silicon Oxide is known to have cubic symmetry. Repeat all of the above experiments on bismuth silicon oxide. Compare your results with those for the $BaTiO_3$ crystal and explain the differences in each case. What is your estimate of the relative photorefractive writing speed of $Bi_{12}SiO_{20}$ vs $BaTiO_3$ for the same write laser power?

5.2.10 Summary (optional)

Given your results and observations in the experiments above in addition to all the other reading you have done concerning the photorefractive effect, and in particular the manifestation of this effect in $BaTiO_3$, write three or four paragraphs summarizing the highlights of this fascinating phenomenon that would be exciting to a typical layman who would read a journal at the level of Scientific American.

Computer operating instructions

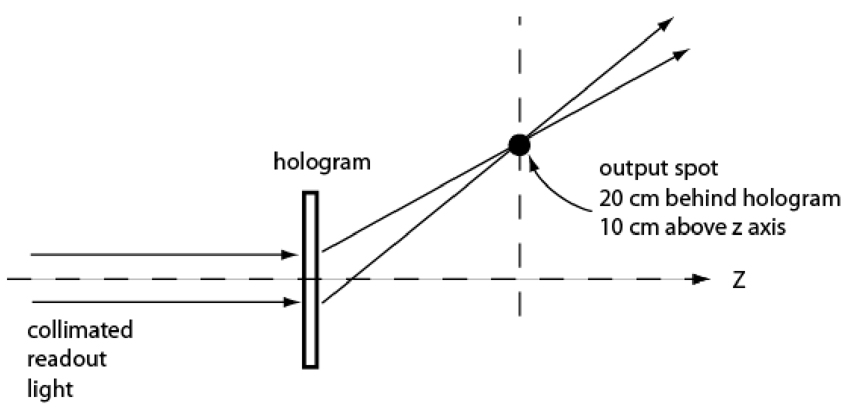
VI folder
Advanced data logger
Advanced data logger
Device 1 (computer channel)
Digits of precision: 5
Channel: 0
Run
Save
Enter header text
Use matlab script to read VI file.

5.3 Designing and Making Holograms

Hologram Options

(a) Make a Holographic Optical Element
In this session you will see an example of a holographic optical element. The element was designed to act as a reflection hologram, taking collimated light and producing a focused off axis beam. For this writing project you will use what you know about holography and the holographic writing process to design a Holographic Optical Element (HOE) with the following characteristics:

Goal: Focus a collimated beam to an off-axis spot
Read Wavelength: 514nm (Argon-ion laser green line)
Write Wavelength: 632.8 nm
A diagram of the desired system is shown below.



The most interesting aspect of this project is the complication introduced by using a different wavelength light to write the hologram than is used to readout the hologram. Detailing how you addressed this complication should be a major focus of your report.

(b) Make a hologram of a magnifying glass in front of an object
For this option you will make a multiple beam hologram of an object located beyond a magnifying glass. For the purposes of this assignment the position of the glass and object should be set to generate a virtual image of the object when observed from the location of the hologram plate.

An interesting question to ask about this system is what happens when you read out with a conjugate of the reference beam without the magnifying glass in the system? For a hologram made without a magnifying glass when the hologram is read out with a conjugate of the reference a real image forms at the location of the object. In the system described for this option do you form a real image when using a conjugate readout? What about when you return the magnifying glass to the system? Addressing these questions should be a major focus of your report.

(c) Make a more complicated hologram
Most of the more interesting examples of art holography, at least from a technical point of view, are made using systems significantly more complicated than the two beam hologram made in class. For this option you will design and make a more complicated hologram. Some examples include multi-beam reflection or transmission holograms (more than two beams), rainbow holograms, white light transmission holograms, multiplexed holograms, multiple exposure holograms, and pseudo-color holograms.

More complicated hologram geometries can result in more interesting holograms. In your report you should address why you chose the hologram geometry used to make your hologram. In particular, what does this hologram geometry allow you to achieve, either in readout or writing that you cannot duplicate with a simpler hologram. You should also present a brief summary of the history of the type of hologram you choose to make.

Further Instructions for your Report

For all options, your report should include:
(1) A brief (1-2 paragraph) discussion of holography in general
(2) A discussion of the design of your hologram including diagrams of the systems used to write and readout your holograms
(3) Experimental details of the exposures, beam intensities, and recording material
(4) Details of experiments you used to answer the questions posed by your chosen topic

The Lab will be set up for holography for a full week after the holography lab session ends to give you time to design and build the hologram recording system for experiment .2. Recording holograms can be difficult, and it is possible you will not make a successful hologram with your system. In this case, your paper should address why you think the system you built did not work.

APPENDIX 1.

Instructions for the Development of Photographic Film and Plates

For the holography lab we will normally use one of two developers, and one of two hologram emulsions. The two developers used are JD-2 and JD-4 kit developers, and the holographic emulsions commonly used are PFG-01 and PFG-03M.

Developer Details

JD-4 and JD-2 are developer kits (developer and bleach) made by Photographers Formulary (stores.photoformulary.com), and commonly purchased through Integraf (www.integraf.com). Either developer can be used with either holographic emulsion, but the JD-4 developer is normally used with the PFG-03M emulsion. The two major differences in the developers are: (1) the exposure energy and (2) the develop time. When using JD-4 developer the exposure energy is about one-tenth the energy required when using JD-2 developer. The develop time when using JD-4 is about 20 seconds, but the develop time when using JD-2 is about 2 minutes.

The kits contain the powdered chemicals to mix both the developer and associated bleach. The developer is mixed as two parts, A and B, which are kept separate until just before use. After mixing the A and B liquids the developer will ‘go bad’ in 20min (JD-4) to about 2 hours (JD-2), so we generally mix parts A and B just before loading a plate in the system.

Developer parts A and B will keep for a few months at room temperature, and longer in a refrigerator. Developer mixed for the holography lab can generally be used for final projects, but a new kit should be purchased each semester the class is run.

The JD-4 kits come with a copper-sulfate-based bleach that seems to work a little better than the Potassium Dichromate bleach in the JD-2 kits. Holograms bleached with JD-2 bleach tend to darken to brown over time faster than the holograms bleached with the JD-4 bleach.

Emulsion Details

The two most commonly used holographic emulsions for 6.161 are PFG-01 and PFG-03M. Both types are designed to be operated with red light. In this lab we will expose the plates using a red Helium-Neon laser (632.8nm). The emulsion layer in the PFG-01 plates is 7-8 microns thick, while the emulsion layer of the PFG-03M plates is 6-7 microns thick. The major difference between the two emulsions is the size of the silver halide grains used to record the holograms. The PFG-03M emulsion has the finer grains of silver halide and these require higher exposure energy for proper hologram recording. The different recording energies for the two emulsions and two developers are given in the table below.

Table I. Exposure energy for developer/emulsion combinations. Note that the exposure for PFG-01 is given in microjoules/cm^2 while the exposure for PFG-03M is given in millijoules/cm^2.

Hologram Emulsion	JD-2 Exposure Energy	JD-4 Exposure Energy
PFG-01	80 microjules/cm^2	Unspecified
PFG-03M	1.5 mJ/cm^2	0.15 mJ/cm^2

Writing/Developing Process (JD-4 with PFG-03M)

1. The recording plate is mounted in the plate holder, and the system is allowed to stabilize for 1-3min.

2. The exposure is made. The exposure time is set to achieve ~300 microjoules/cm^2. This is twice the manufacturer specified exposure, but in practice seems to work well.

3. The plate is developed for 20s in JD-4 developer.

4. The plate is rinsed for 3min in a tray of distilled water (obtained in building 13).

5. The plate is bleached in JD-4 bleach. The plate is bleached until it is clear, and then ~20s longer.

6. The plate is rinsed again for 3min in a tray of distilled water.

7. The plate is dipped into a solution of ~1/2 capful of Kodak Photoflo + 0.5 L distilled water. The photoflo is a wetting agent that helps the plate dry without spots.

8. The plate is then air dried standing vertical (for as long as you can wait), and finished with a heat gun.