Department of Electrical and Computer Engineering
University of Colorado at Boulder

OPTICS LAB - ECEN 5606

Experiment No. 2
INTERFEROMETERS

Revised 1/11/93 KW, Edits 2/10/04 RM, Revised 1/17/08 SRPP, KW 1/17/10

I. Introduction

This experiment is intended to familiarize you with interferometric systems, and the special care that must be used to obtain good interference. It will also familiarize you with lasers, spatial filters, collimators, mirrors, beam splitters, optical mounts and tables, etc. You will set up a Twyman-Green (Michelson) interferometer, that will be used to characterize the coherence length of the He-Ne laser. Then you will set up a Mach-Zehnder interferometer that will be used to measure the surface flatness and optical homogeneity of a test object of your choice. Finally, you will set up a polarization interferometer that demonstrates the coherent vectorial nature of laser light.

II. Background

When two mutually coherent beams pass through each other, we can observe the phenomena of interference between the wavefronts. An interferometer is, in the broadest sense, a device which generates interference fringes, either temporal or spatial. Interferometers can basically be classified into two types: wavefront-splitting interferometers and amplitude-splitting interferometers. Wavefront splitting interferometers, like the double slit, recombine two different parts of a wavefront to produce fringes. Amplitude-splitting interferometers, on the other hand, divide a wavefront into two beams (splitting the amplitude) which propagate through separate paths and are then recombined. Typically, beam splitters are used for splitting and recombining wavefront amplitudes, but in some cases gratings or crystals can be used instead. If we use a monochromatic coherent source we can determine the difference between the propagation characteristics of the two paths, so that a lens can be compared with a master, or a test object can be checked for optical flatness. Alternatively, we can determine the coherence length and spectrum of a source by varying the path length difference between the two arms.

III. Preparation

Read the chapter on interferometers in your favorite optics book, some suggested references are:

Born & Wolf, Principles of Optics, 7.5
Hecht & Zajac, Optics, 9
Jenkins & White, Optics
Moller

Choose an object which you wish to measure its optical flatness and bring to your lab sessions.

IV. Prelab

1. Two Lorentzian-shape laser lines with very narrow line widths and with center frequencies separated by c/2L = 435 MHz drift through a Doppler-broadened gain line with FWHM= $2\Delta\nu_L$ = 500 MHz. See Fig. 1 below. What do you expect the fringe visibility function to be when the two lines are symmetrical about f_0, and as they drift away from this condition? (Look at Table I for coherence lengths of typical sources.)

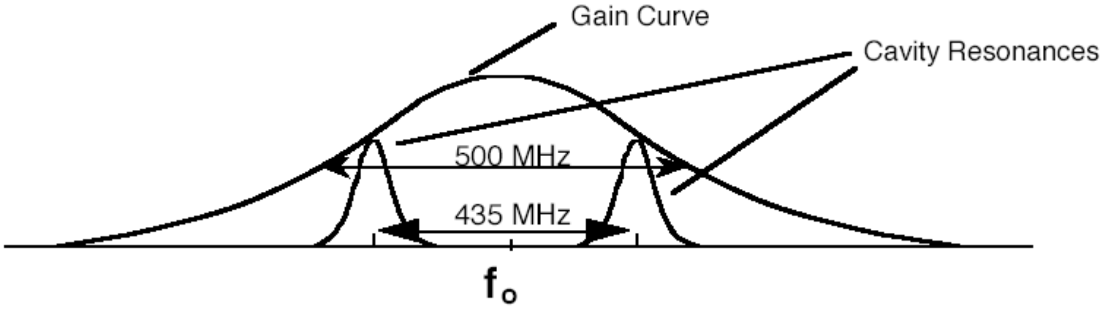

Fig. 1

Source Type	Mean wavelength [nm]	Bandwidth [nm]	Coherence length
Hg arc (high pressure)	546.1	10.0	< 0.03 mm
Hg arc (low pressure)	546.1	1.0	< 0.3 mm
Ag laser	544.5	~.009	< 3 cm
He-Cd laser	441.6	~ 7 x 10^{-4}	< 27.5 cm
He-Ne laser	632.8	10^{-5} to 10^{-6}	~ 10^4 cm

Table I

2. If the mirror in the Twyman-Green interferometer is moved at 1 cm/sec., what temporal frequency beat do you expect on the output when illuminated with a He-Ne laser ?

3. The index of refraction of air is

$$n = 1 + .003\,\frac{P}{P_O} \bullet \frac{T_O}{T}$$

where P_o = 760 torr, T_o = 293°K, P is the pressure, and T is the temperature. What temperature rise is necessary to produce a dark to light transition if a 10 cm wide hand is held under one arm of a Mach-Zehnder interferometer?

4. A *Hartman* wavefront sensor is a simplified version of the *Shack-Hartman* used in the lab to measure and characterize wavefronts that is based on a simple pinhole array suspended above a CCD detector array without a lenslet array. Consider a 1-D version in which a slightly quadratically curved wavefront impinges on an array of pinholes of 25um diameter spaced by 1mm across a 1cm aperture suspended 1mm above a CCD array with 5um pixels.
    a. When used at 632.8nm, how does this 1mm distance compare with the confocal distance, and will you see substantial diffraction over this distance?
    b. If the wavefront curvature needs to produce 1 pixel of motion in order to be detected, then what is the minimum curvature that can be measured?

c. Can the position of the diffracted spot from the pinhole be determined to subpixel accuracy, and if so how? Assuming that we can accurately determine the position to 1/100 of a pixel, what is the minimum wavefront curvature that can be measured?

V. Equipment

-He-Ne laser
-CCD camera, digital oscilloscope
-Spatial filter with translation stages
-Non-polarizing cubes and plate beamsplitters, polarizing beamsplitter
-2 mirrors, collimating and expanding lenses, lens used for CCD camera
-Iris
-A box of ND filters
-Polarizer, (1/2)λ(half wavelength) plate
-Lens and mirror holders, posts and magnetic bases
-Rail
-Test object

VI. Procedure

1. **Spatially filter the laser** .

Turn on the He-Ne laser and Z-fold onto the rail. Make sure the beam is parallel to the table and centered on the rail by using an iris stopped down as far as it will go that you slide along the rail. Spatially filter the beam. Practice this; you will be doing it throughout the semester and you should be able to do it quickly. Is the beam still parallel to the table? It is hard to tell, but try to readjust the spatial filter until the expanding beam is not deviated. How do you do that?

a. Hint #1: Before aligning the spatial filter, remove the pinhole and adjust the microscope objective until it does not deviate the beam.

b. Hint #2: To accomplish Hint #1, set an iris in front of the spatial filter and adjust its height until the beam is exactly centered. Do the same thing with a second iris. Now use these as measuring tools.

After the adjustment of the spatial filter, you should get a round, uniformly illuminated pattern with minimized diffraction fringes (rings).

2. **Collimate the laser beam** .

Now collimate the beam with a lens, once again keeping the beam path from being deviated. Center one of your irises (from step 1) in the beam just after the pinhole. Look at the back reflections from the lens, and adjust until they are symmetrical around the iris, while keeping the beam undeviated if possible. A paper target with a very small hole taped to the iris can help you see the weak back-reflections from the lens.

a. How do you tell if the beam is collimated? (Hint: if a collimated beam is reflected by a flat mirror back onto its aperture it should remain the same size as the aperture.)

b. Is this an accurate way of collimating the beam? (Hint: the farther away the flat mirror is placed from the aperture the better the chance of detecting any divergence). You now have a well aligned, collimated beam.

c. Verify and optimize your collimation using the wedged shear plate. A slightly diverging (or converging wave will produce two virtual sources from reflections of the front and back surfaces of the shear plate that will be slightly displaced due to the thickness of the tilted plate and will therefore produce linear fringes in the direction of the tilt. As the focus is adjusted to a collimated condition these two virtual sources move to infinity and the fringe spatial freqbuency along this axis decreases towards zero at which point the slight wedge of the collimation tester in the orthogonal direction becomes apparent since it is angled to produce about 5 fringes across the aperture. So as you approach collimation, the high frequency fringes will rotate by 90 degrees to align parallel to the black line with 5 straight fringes. Any residual curvature represents aberrations implying that you need to tilt and center the collimating lens more precisely to minimize the off-axis aberrations.

d. If the collimating lens has obviously different radii of curvature, its orientation matters – which orientation is better and why? You should experimentally verify this by flipping the lens around and looking at the straightness of the fringes produced by the shear plate collimation tester.

3. **Shack Hartman wavefront sensing** .

Shack-Hartmann (SH) wave front sensing is a non-interferometric method of measuring a beam's wave front extremely precisely and quantitatively. A SH sensor contains a two dimensional micro lens array precisely aligned in front of a CCD detector. A beam's wave front is measured from the displacement of the array of focal spots produced by the local wavefront tilts incident on the micro lens array. The goal of this section is to analyze your collimated beam with a SH sensor and obtain quantitative information on the beam collimation. Place an iris after the lens, and close it down to ~1cm diameter. Now, place the SH sensor ~1m (or as far as possible) away from the iris (important for alignment). Use a USB cable to connect the SH sensor to a computer that has the CLAS-2D software installed on it. Align the SH sensor as described in the section 2.3 of its manual. Measure the wave front using the CLAS-2D software. For measuring, first click "Acquire Data" under the "Action" menu, and then click "Compute Wavefront", which is also under the "Action" menu.

a. Note the P-V OPD (peak to valley optical path length difference) of the wave front. Does the wave front correspond to that of a perfectly collimated beam? Explain. Print a report of your observations by clicking on "Print report" under the "File" menu.

b. Flip the collimating lens around, check for collimation, align the SH sensor, and measure the wave front again. Compare this wave front to the wave front recorded before flipping the lens. Which of the two is less aberrated? Why? As before, print a report of your observations.

c. Move the lens towards the SH sensor by 2cm and measure the wave front again. Explain your observations.

d. Reestablish your best collimation condition.

4. **Twyman-Green Interferometer**.

Set up the Twyman-Green interferometer shown in Fig. 2. Make sure the collimation lens mount has sufficient adjustments for step 5. Make sure the distance from the beam splitter to each of the mirrors is about the same (±1 cm).

a. You can either use a plate or a cube beamsplitter. Which did you use and why? (Hint: how many beam deviating interfaces have to be crossed by the beam in each case?)

b. Center an iris near the collimating lens and stop down to a small aperture. There should be two spots on the screen (or wall) which are reflected from the two mirrors. Tilt the mirrors so that the two spots align on the wall. (You may wish to initially adjust the mirrors and beam splitters to be vertically correct by retroreflecting the raw HeNe back into itself, only change the horizontal adjustment of the mirrors.) Do they also align just after the beamsplitter, and on the surface of the beamsplitter?

c. Iteratively readjust until you have alignment of the reflected spots on the beamsplitter (near field) and on the wall (far field). (Hint: There are many degrees of freedom in this setup which can be adjusted. You'll find that some adjustments affect the position of the spots on the wall more than at the beamsplitter and vice versa. Think lever arms; you should use this to your advantage.

d. Open up the iris. Do you see fringes?

e. Block one of the arms, do you still see fringes? Do you observe any coherent artifacts?

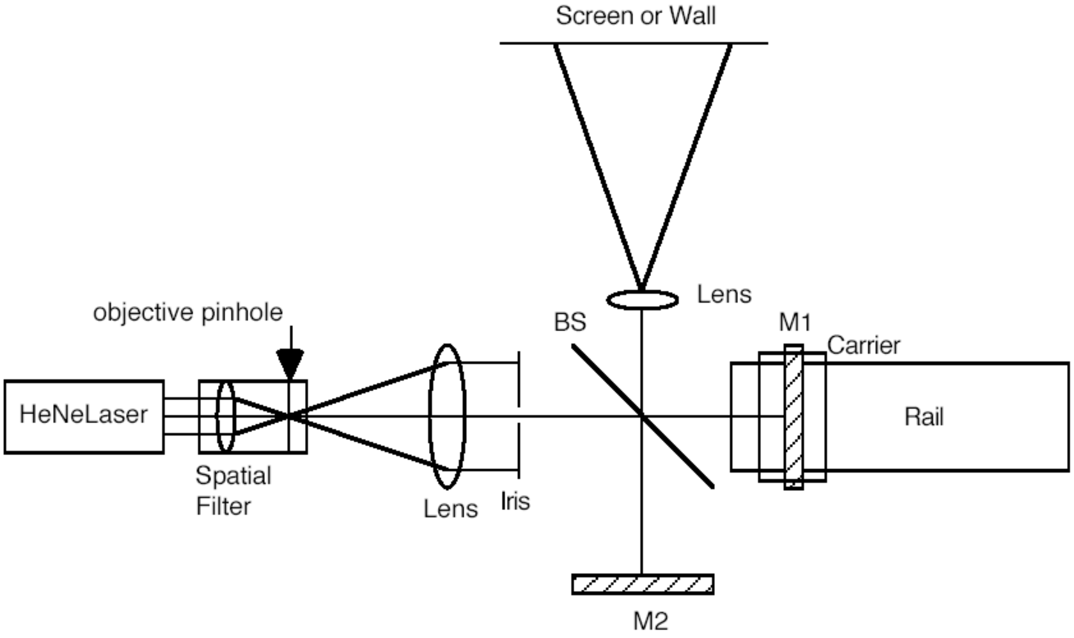

Fig. 2. Twyman-Green Interferometer

5. **Optimizing the fringe flatness**.

Notice that attaining a perfectly uniform interference pattern across the full aperture is virtually impossible due to aberrations and misalignments. Adjust the orientation of the mirrors to minimize fringes. You can use the orientation and the curvature of the fringes as a guide. Slight adjustments in the position of the collimating lens can improve the uniformity. You should use a translational stage for this purpose as it will require very fine adjustment. You can use the curvature of the fringes as a guide. When the fringes are straight lines rather than curves you have nearly perfect collimation. After you have done this there will still be some aberration effects noticeable in the illumination pattern. Stop down the iris to just conceal the last non-uniformity. That is, keep the iris open as far as possible while allowing only uniform illumination through. How big is this unaberrated area? What type of aberrations predominate (i.e., imperfections, spherical aberrations, etc.)?

6. **Align a moving mirror on a rail**.

Now align the rail and translation stage so that you can change the path length of one of the arms with respect to the other while maintaining good fringes. Stop down the iris, now as you slide the mirror back and forth the position of the reflected spot should not move. Open up the iris, now as you slide the mirror back and forth your fringe pattern should not change much. The fringe pattern will, however, go through phases of poor and good definition as the mirror is moved and this is normal. It is a result of the periodic coherence function of the laser

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7. **Measure the laser coherence function** .

Slightly adjust a mirror in order to get clean vertical fringe pattern. Shine it on the CCD camera focal plane without the CCD lens. You may need to use ND filters to avoid saturating the CCD camera.

a. Hook the output video signal from CCD camera to both a monitor and a digital oscilloscope. Determine the dark level from the CCD camera.
b. Starting from the same path lengths of the two arms, measure the contrasts of the fringe pattern as the difference of the path length increases. Plot the coherence function of the laser.
c. What is the 90% coherence length? What is the 50%coherence length? Can you say anything about the spectrum of the laser?

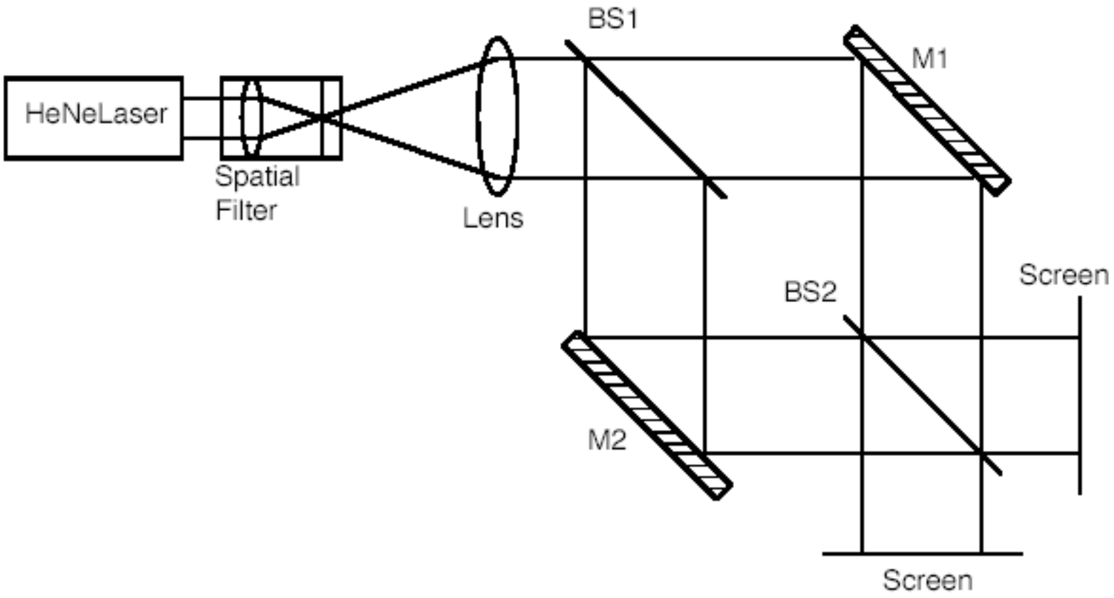

Fig. 3. Mach-Zehnder Interferometer

8. **Mach-Zehnder interferometer** .

Set up the Mach-Zehnder interferometer shown in Fig. 3 . Stop down the iris and align the two beams on the output beamsplitter. Are they aligned on the wall? Adjust the orientation of the output beamsplitter to have the two beams overlap on both of the walls. Iteratively optimize this adjustment to make the beams after the output beamsplitter parallel and overlapped. Open the aperture, did you get fringes?

9. **Beamsplitters, Coherent Artifacts, and Aberrations** .
   a. Which beamsplitters did you use? Do you see any coherent artifacts due to the beamsplitters? (i.e., - something constant as opposed to the shifting fringe pattern.)
   b. Draw a picture that explains what you think is causing these artifacts. Can you explain the modulation depth of these coherent artifacts with your model?
   c. Minimize the fringes by adjusting the mirrors. What kind of aberration do you observe?

10. **Fringe motion due to thermal air currents** .

Insert your hand underneath one arm of the interferometer. Watch the interferometer pattern as the air above your hand warms up and a plume rises.

   a. How large a fringe shift is produced? From your prelab answer what temperature rise does this correspond to?
   b. Put your hand underneath the beam before the first beamsplitter. Any fringe motion, why?

11. **Floating optical tables** .

Observe the stability of the fringes with the table floating. Now turn off the air and lift a corner of the table to bleed the pneumatic isolation cylinders of their air reserves.

Now observe the fringes as your lab partner walks around or touches the table. In particular, note the different response to high frequency disturbances, such as tapping a ball driver on the table top, and low frequency disturbances, such as giving the table a slow gentle shove. Note your observations and conclusions. Turn the air back on and refloat your table.

12. **Two outputs of the interferometer** .
    a. Simultaneously observe both output ports of the interferometer. What do you notice? What general principle is illustrated here?

    b. Is there any way of violating this condition, say by changing the phase upon reflection of the dielectric mirrors. You may wish to work out the math as a prelab exercise.

13. **Orthogonal polarization interferometer and quantum erasers**
    a. Measure the laser polarization using a polarizer or Brewster test. Put a half - wave plate in front of the first beamsplitter, rotate it and see if there is any changes on the interference patterns on the two screens.

    b. Now adjust the polarizer to rotate the laser polarization to a 45° angle. Replace the first beamsplitter with a polarizing beamsplitter, and realign the interferometer. Do you see any fringes?

    c. Is there any way to get fringes with this set up? Describe how and demonstrate it.

    d. Can you reverse the contrast of these fringes? Can you optimize the modulation depth? Is it possible to violate the condition observed in Step l2. by using both output ports of this interferometer? Why doesn't this violate the general principle illustrated in Step l2?

14. **Precision Interferometric measurement** .

Have the Prof or TA let you in to the room with the Wyko 6000 phase shifting interferemeter. This precision instrument measures up to 6" diameter optics, and can test for planarity, sphericity, or other conic sections with an amazing precision using phase shifting interferometry by moving the reference flat with piezo translators through a fringe to demodulate the phase from the fringe pattern. It can plot a wavefront error, decompose into Zernike polynomials, or perform additional analysis. The fringes are speckle free due to an internal speckle eater (rotating diffuser) follower by a zoomed imaging system onto the camera.

a. See if the table is floating, and turn on the air above the table if it is not. Turn on the PC on the rack and the stabilized HeNe key (leave it in *Frequency Stabilized Mode*)., or if the system is on, just wake the PC from the keyboard. The stabilized HeNe takes a while to warm up and stabilize, so you may see drifting fringes initially.

b. The reference flat should already be installed, block the beam leaving the Wyko with a piece of paper. The reference flat can be adjusted by switching the remote from *Test* into Align mode, Clicking on the Yellow icon to bring up the CCD image, adjust the intensity on the remote so you can see two spots, then using the tilt screws on the Wyko exit port bring the two alignment spots into coincidence. The cross hairs (*View: Show Cross Hairs*) or cross sections (*View: Cross Sections*) can assist. Then remove the piece of paper and you should see additional spots due to the alignment of the test flat, you may need to further increase the intensity. Using adjustments on the remote test flat bring all 3 (or 4) spots into coincidence. The system is now prealigned well enough to see fringes.

c. Turn back to test mode and you should be well enough aligned to see fringes. If your fringes show red they are saturated, turn down the *Intensity*. Then adjust the tilts on the remote reference flat. Notice the near perfection of these linear fringes. Air currents can be a problem, but it is fun to place your hand under the double passed beam. Adjust to get as few fringes as possible, and estimate the flatness of these 6” optics. You can configure the *Measurement Options* by clicking on the paper icon with a red dot, then perform a measurement by clicking on the paper icon ('New') on the far upper left. Don’t touch the table while it moves the piezo, and takes several frames for phase demodulation, then it reports the wavefront fit. You can get all sorts of diagnostics under *Analysis* menu, including *Zernike*, or under *Other:Options* is a vast array of analysis options including *Seidel*.

d. Insert a test flat object such as the glass plate or the Continental BS cube. Note the alignment platform only loosely sits on the rails and is VERY HEAVY. Block the precision test flat beam and redo the alignment with your new test object. Under *View* drag the windowed intensity to surround your object. Then *Acquire* a wavefront with the left button, perform *Zernike* and *Seidel* analysis. Take a screen image with a camera, since connecting this old instrument up to the lab printer is hard, and get a printout of your camera image for your lab book.

e. When you are done, cover the optics, turn off the table air and let the Wyko go to sleep, but we can leave the laser on for a few weeks.