Michelson Interferometer & Fourier Transform Spectrometry

Introduction

The Michelson interferometer is the best known of a class of mirrored interferometers known as *amplitude-splitting* interferometers. It gained its fame through an experiment of A. A. Michelson and E. W. Morley first published in 1887. In their experiment, a variant of the device used in this experiment was employed to set a limit, consistent with zero, to the velocity of the motion of the earth relative to the "luminiferous aether", the medium in which light was presumed to propagate. The interferometer consists of two mirrors set at right angles and a beamsplitter that divides an input beam of light into two beams of approximately equal intensity. The two beams of light traverse separate paths and after reflection from the mirrors are recombined at the beamsplitter (Fig. 3). If the optical path lengths of the two beams do not differ by too much, an interference pattern is produced. The beamsplitter in this experiment is a cube-type beamsplitter. It has the advantage that both beams traverse the same amount of glass so that the optical path lengths (the optical path length is nl where l is the physical path length and n is the index of refraction) of the two beams are the same when the physical path lengths are the same.

A Fourier transform spectrometer uses the same basic configuration of mirrors and beamsplitter as a Michelson interferometer, but one of the mirrors can be moved rapidly back and forth. The recombined beam is detected synchronously with the motion of the mirror. This has several advantages. For a broad-spectrum source, the whole spectrum is effectively being observed at each mirror position. Also, the detected DC light signal in the Michelson interferometer is converted to an AC signal at the frequency of the mirror motion. If the signal is noisy as a result of fluctuating background light, the frequency of the mirror motion can be chosen to be at a portion of the frequency spectrum for which the background fluctuations are less than at DC. In practice, mirror motions at a few tens of hertz will result in substantial noise reduction since noise amplitudes often drop off as $1/f$ or faster (f = frequency). Fourier transform spectrometers are used primarily in the infrared portion of the spectrum. This choice is made in part because of the difficulty of maintaining mirror parallelism to within a fraction of a wavelength when one of the mirrors is vibrated and in part because noise reduction is a more serious problem in the infrared.

The name, Fourier transform spectrometer, comes from the fact that the intensity $I(\Delta)$ of the recombined beam as a function of the path difference for light from the two arms, Δ, is the Fourier transform of the intensity of the light source, $I(\sigma)$. σ is the wavenumber of the light and is simply the inverse wavelength, $\sigma = 1/\lambda$ or by the free-space relation $c = \nu\lambda$, with ν being frequency and c the speed of light, $\sigma = \nu/c$. Note that Δ has the dimensions of length while σ has the dimensions of inverse length. This is typical of a "transform pair", the variables in terms of which a function and its Fourier transform are expressed. To summarize, $I(\Delta) = F\{I(\sigma)\}$. That is, $I(\Delta)$ is the Fourier transform of $I(\sigma)$.

We can see why this relationship is true by considering the following argument. If the light source is monochromatic and the two beams are of equal amplitude, the amplitude of the combined beam can be written in complex form as $E_T = E_0 e^{i\omega t} + E_0 e^{i(\omega t+\delta)}$, where δ is the phase difference between the two beams that results if they traverse paths of different lengths before recombining. For a path difference Δ the phase difference is $\delta = 2\pi/\lambda\Delta = 2\pi/\lambda[2(l_1 - l_2)\cos\theta]$. The value shown for Δ is derived for light incident on the interferometer plates at angle θ to the normal and a difference

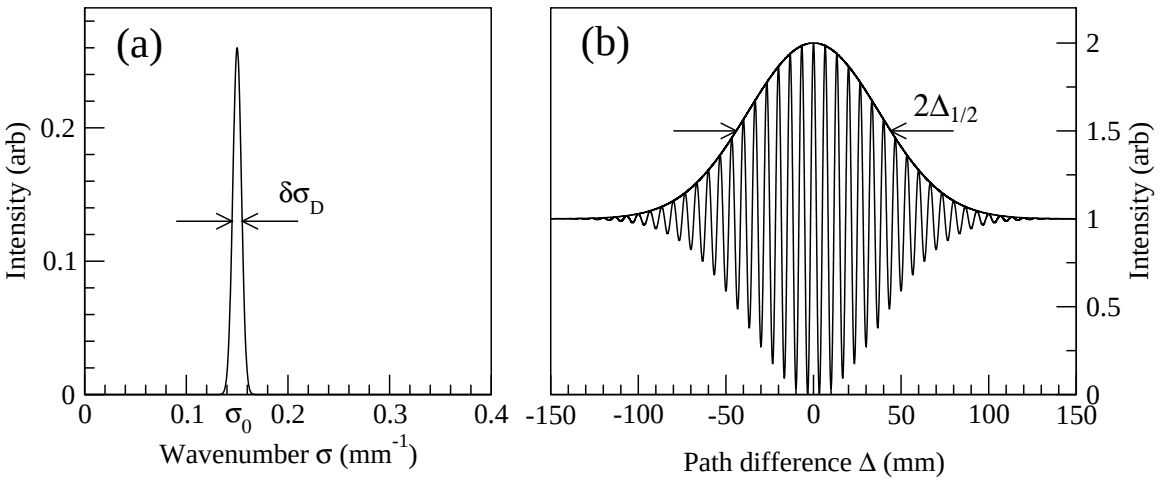

Figure 1: A single Gaussian "line" and its Fourier transform. (a) The line has a central wavenumber $\sigma_0 = 0.15$ mm^{-1} and a full-width at half maximum $\delta\sigma_D = 0.01$ mm^{-1}. (b) The Fourier transform of the line, Eq. (2), has a Gaussian envelope of FWHM = 88 mm.

in the length of the arms of $l_1 - l_2$. The intensity of the combined beam can then be written $I = |E_T E_T^*| = I_0(1 + \cos\delta) = I_0\,(1 + \cos(2\pi\sigma\Delta))$.

If the light source is not monochromatic, but has a spectral distribution given by $I(\sigma)$, and the light at different wavenumbers σ is incoherent, i.e., has a random phase difference, then the total intensity can be found be adding intensities for different σ:

$$I(\Delta) = \int_0^\infty I(\sigma)\,(1 + \cos\,(2\pi\sigma\Delta))\;d\sigma\;. \tag{1}$$

To within a constant, the right-hand side is nothing more than the cosine form of the Fourier transform of $I(\sigma)$ so we have succeeded in writing an explicit form of the relation $I(\Delta) = F\{I(\sigma)\}$. [Note: You will probably be more familiar with "wavenumber" defined as $k = 2\pi/\lambda = 2\pi\sigma$. Spectroscopic data for the most part is still expressed in terms of the older "wavenumber, $\sigma = 1/\lambda$, so that will be used in this experiment write-up].

One of the lamps used in this experiment is called a gas-discharge lamp and its output results from an electrical current run through an inert gas such as neon and a vapor of the substance, sodium for example, which gives the desired spectrum. The atoms of the vapor have a Maxwellian velocity distribution (also a Gaussian) along any line of sight. If stationary they would all emit at the same wavenumber, but the light from those moving toward the observer will emit at a wavenumber Doppler-shifted upward and those away at a wavenumber shifted down. Since the shift in σ is proportional to v/c and the velocity distribution is Gaussian, the wavenumber distribution will also be Gaussian. In a practical lamp the effects of gas pressure and electrical current lead to additional broadening so the spectral distribution is distorted and broadened beyond its ideal Doppler shape. Nevertheless, we will consider just a Gaussian shape for mathematical simplicity.

Two examples of spectral distributions will be given that illustrate Fourier transforms of special interest and give helpful clues as to the information obtainable from Fourier transforms. The first distribution is Gaussian:

$$I(\sigma) = I_0 e^{-\frac{4\ln 2(\sigma-\sigma_0)^2}{(\delta\sigma)^2}}$$

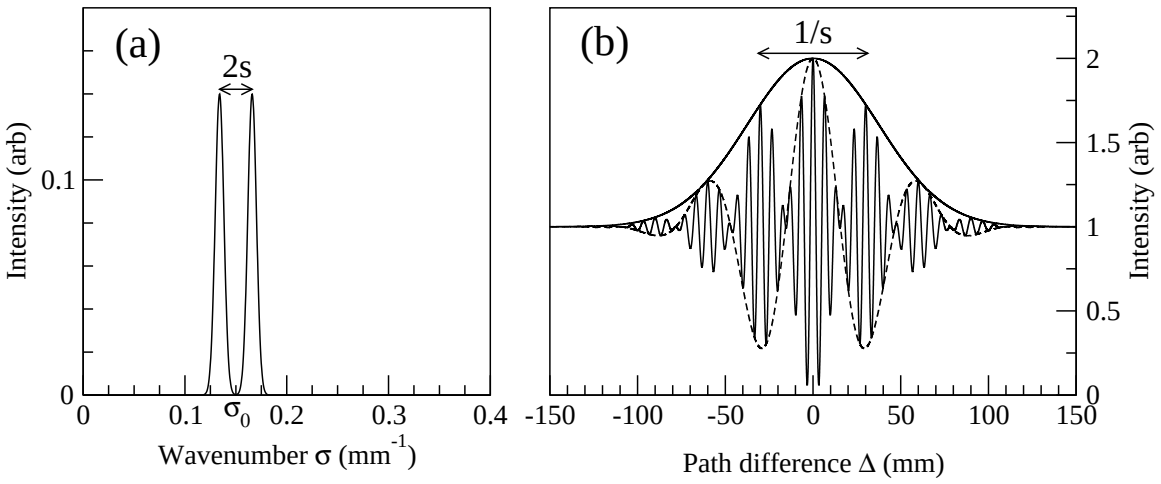

Figure 2: Two Gaussian lines and its Fourier transform. (a) The lines have central wavenumber $\sigma_0 = 0.15$ mm^{-1} and wavenumber separation $2s = 0.032$ mm^{-1}. Each line has a full-width at half maximum $\delta\sigma_D = 0.01$ mm^{-1}. (b) The Fourier transform of the lines, Eq. (4), has a Gaussian envelope (solid line) of FWHM = 88 mm, and a cosine envelope (dashed line) $1/s$ of wavelength 62.5 mm.

where I_0 is an intensity normalization, σ_0 is the wavenumber for the center of the spectral distribution and $\delta\sigma$ is the width. When $\sigma - \sigma_0 = \frac{1}{2}\delta\sigma$, the intensity is at half its maximum value. For this reason $\delta\sigma$ is described as the full width at half maximum (FWHM) of the distribution.

The Fourier transform of a Gaussian is another Gaussian (Hecht p. 521). This leads to an expression for the intensity of the combined beam of the Michelson interferometer when the source is a single Gaussian spectral line:

$$I(\Delta) = I_0' \left(1 + e^{-\frac{(\pi\,\delta\sigma\,\Delta)^2}{4\ln 2}} \cos(2\pi\sigma_0\Delta) \right) . \tag{2}$$

The cosine term describes a rapid oscillation in intensity as the mirror is moved and its manifestation is the fringe pattern you will observe in this experiment. A change in path length of $\lambda/2$ is sufficient to take the intensity from a maximum to a minimum. The exponential varies much more slowly. It is a maximum for zero path difference and drops to half its maximum value for a path difference

$$\Delta_{1/2} = \frac{2\ln 2}{\pi\,\delta\sigma} . \tag{3}$$

An important point to note here is that the narrower the line (the smaller $\delta\sigma$) the greater distance the mirror must be moved to reach the half-intensity point. An example of such a line and its transform is shown in Fig. 1. [Note: the example uses wavenumbers well outside of the visible range.]

The second example is a spectrum consisting of two equal-intensity Gaussian lines centered about wavenumber σ_0 and separated by a wavenumber difference $2s$; this is the situation encountered in the case of the sodium lamp which has two closely spaced yellow lines that contribute to its bright yellow color. The Fourier transform of this spectrum is the same as that for a single Gaussian multiplied by an additional term $\cos(2\pi s\Delta)$. This term goes from a maximum through a minimum

to a new maximum when Δ goes from 0 to $1/(2s)$. The full expression for the intensity is

$$I(\Delta) = I_0' \left(1 + e^{-\frac{(\pi\,\delta\sigma\,\Delta)^2}{4\ln 2}} \cos(2\pi\sigma_0\Delta)\cos(2\pi s\Delta)\right) . \tag{4}$$

Thus, for this spectrum the intensity (1) oscillates rapidly as the mirror is moved by $\lambda/2$; (2) is modulated periodically when the mirror is moved an additional amount $1/(4s)$. (Note: the change in path length Δ is *twice* the distance the mirror is moved); and (3) finally dies away as the difference in path length gets much larger than $\Delta_{1/2} = 2\ln 2/(\pi\,\delta\sigma)$. Note again the inverse relationship between the spectral separation and the distance the mirror must move for the intensity to be affected by that separation. One variation goes as $1/\sigma_0$, another as $1/s$, and a third as $1/\delta\sigma$. These features are illustrated in Fig. 2, where we see that the intensity contrast is modulated by both the slow Gaussian envelope and the more rapid cosine envelope.

The cosine modulation in the intensity pattern can be understood as an example of "beats" that one hears when two tuning forks of nearly the same musical note are sounded simultaneously. In that case, the variation of intensity is over *time*; in the case of the interferometer, the variation in contrast is over *space*–the value of Δ. In the acoustic example, the beat frequency is equal to the *difference* in tuning fork frequencies, and in the optical example, the "beat wavenumber" is equal to the *difference* in the wavenumbers of the two lines.

References

1. Hecht, *Optics* (5th ed.), Chapter 11, Fourier Optics; Chapter 12, Basics of Coherence Theory; 9.4 Amplitude-Splitting Interferometers, 9.4.1 Fringe classifications, 9.4.2 Mirrored Interferometers; 9.5 Types and Localization of Fringes.

2. James, *A student's guide to Fourier transforms, 2nd ed.*, pp. 76–85.

3. Anne P. Thorne, *Spectrophysics* (2nd ed.), pp. 185–196, Fourier transform spectroscopy.

1 Experiment

1.1 Alignment and Observation of Laser Fringes

Turn on the sodium lamp at this time to allow it to warm up. You will need to use it after you complete this section.

Turn on the laser. If the previous group has left the apparatus in place, such as the beamsplitter, mirrors and microscope objective, unclamp the magnetic bases from the table and set them aside for now. Your first task is to align the laser.

Check that the laser beam is parallel to the table surface at a height of 6 inches. This is done by shining the laser beam onto the (small) viewing screens, all of which have a horizontal line at 6 inches height. Use two screens: place one as close to the laser as possible, and the other far away (in front of the movable mirror if it is still setup). If the beam does not hit the close screen on the 6-inch line, adjust the *front* positioning screws (on the underside of the laser mount, toward the beam end of the laser) so that the beam hits the line. Now remove the close screen and look at where the beam hits the far screen. Adjust the *rear* positioning screws (toward the power line end of the laser) so that it does. Repeat this procedure (screen close to laser, screen far away from laser) until the beam hits the 6-inch line on both screens.

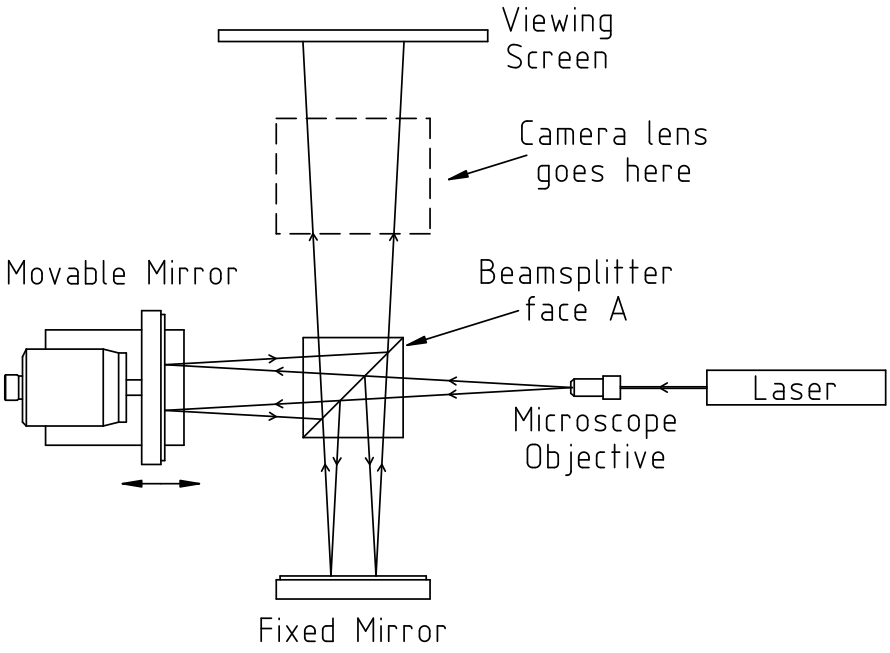

Figure 3: The Michelson interferometer.

The basic configuration of the Michelson interferometer is shown in Fig. 3. The goal in positioning and aligning the interferometer components is to make all optical surfaces perpendicular to the table, and parallel or perpendicular to each other. This is most simply accomplished by observing the reflections of the laser beam from the various optical surfaces, and bringing them into coincidence on a viewing screen.

Check that the position of the interferometer components is as follows; adjust positions as necessary:

The beamsplitter mount should be positioned so that the laser beam strikes face A of the beamsplitter near its center, and so that the clamping (ON/OFF) screw on the beamsplitter base is directly above a row of holes along the narrow dimension of the table. The distance from this row of holes to the front edge of the laser mount where it contacts the table should be 45-50 cm (the precise value does not matter). Place the large viewing screen 15 to 20 cm from the beamsplitter face, as shown in Fig. 3, and place the smaller viewing screens at the positions of each mirror, roughly 15 cm from the other faces of the beamsplitter prism. With the beamsplitter base unclamped from the table, rotate the base and use the two vertical adjust knobs (silver ones on underside of beamsplitter platform) so that the directly reflected beam falls on the laser exit aperture, and the "split" beams are at the 6 inch level on all of the viewing screens. Clamp the beamsplitter base to the table, and then make fine adjustments so that the spots are as well centered as you can make them.

Be careful not to touch or contact the mirror surfaces in any way – they are easily damaged.

IMPORTANT: your goal in placing the mirrors is to make them the same distance from each face of the beamsplitter. If you do not do this, the experiment will not work. The mirrors should be positioned as shown in Fig. 3 with the laser beam striking each mirror near its center. The distances of both mirrors from the center of the beamsplitter should be

as close to equal as you can determine with a ruler (measure from the mirror mount surface *NOT the mirror surface itself!*). Around **20 cm** is a reasonable choice. The translation stage micrometer should be set close to a reading of 12 mm on the black scale (Use the black scale for all readings in this experiment). Once the mirrors are suitably positioned, clamp their bases to the table.

Place each of the two small screens between the beamsplitter and each mirror. Double-check to make sure that the beamsplitter cube is still properly aligned. Then remove one of the small screens and adjust the "V" and "H" knobs on the mirror to bring the spots on the viewing screen into alignment. Replace the small screen, remove the other one, and repeat the "V" and "H" knob adjustment. Finally remove both screens. You should see a single bright dot on the big viewing screen with no significant side dots. (Because of interference, you may see fringes within this bright dot.)

Position the microscope objective in the beam path close to the beamsplitter. The front of the objective should be about 1 cm from the cube face. Adjust the position so that a symmetric disk of laser light exits the microscope objective, passes through the beamsplitter and falls on the center of the movable mirror. The image of the beamsplitter cube should be easily visible on the screen and symmetrically illuminated.

If you have aligned the mirrors carefully and set the distances from the beamsplitter to be close to equal with the ruler, you should see curved or circular fringes. Turn the micrometer on the movable mirror; you should see the spacing between the fringes change. Note: two turns of the micrometer thimble move the stage 1 mm. Each fine division on the thimble represents a displacement of 0.002 mm (= 2 microns).

Use the fixed mirror tilt adjustment screws ("V" and "H") to produce a symmetric ring pattern on the viewing screen. Observe what happens when you change one of the fixed mirror tilt adjustment screws in one direction and then the other direction. Do this again with the other tilt adjustment screw on the fixed mirror. Finally try this with the adjustment screws on the translating mirror.

With the ring pattern centered, use the micrometer adjustment to move the mirror on the translating stage so that the fringes are as widely spaced as possible. (Ideally, the ring diameters would go off to infinity, but you will still see some nonzero curvature because of imperfections in the optical equipment and alignment.)

Write down the micrometer setting (roughly) for this location so you can go back to it easily. Then move the mirror through this spot and note how the fringe spacing changes as you pass back and forth through it.

Now, move the mirror all the way to the extreme settings on the micrometer. **Translation of the stage should not exceed the limits of 0 and 20 mm on the black scale (5 and 25 mm on the red scale).** Observe what happens to the ring pattern. Do the fringes ever disappear? They should if the difference in path length is larger than the coherence length of the laser. You should be able to predict whether the pattern should disappear: assume the spectrum from the laser consists of two equal-intensity Gaussian-shaped lines with full width at half maximum of 500 MHz separated from each other by 687 MHz. Calculate the coherence length of such a source. (This is close to the actual spectrum from the laser. The laser often operates simultaneously in two longitudinal modes separated by 687 MHz. The line width of a single mode arises from random fluctuations about a central frequency.)

For your report: Describe your observations of the ring pattern as you translate the mirror over a wide range of settings.

Estimate by a calculation how far you would need to move the stage until the intensity of successive fringes was half its zero-path-difference value. A handy result of Fourier analysis that is useful in this experiment is the fact that if the frequency spread of a light wave packet is df, the length of the wave packet along the propagation direction is $L = c/df$. A close study of Figures 1 and 2 may also be of some help in understanding the relationship between the range of good fringe contrast and the line width.

1.2 White-Light Fringes

A fringe pattern can be observed for light with a very broad spectrum, but only when the path difference between the two arms of the interferometer is close to zero (mirror surfaces equidistant from the center of the beamsplitter). This zero-path-difference (ZPD) condition will be approached in four steps increasingly sensitive to it. First, look at the laser-light fringes and set the micrometer to the zero-curvature point of those fringes; second, use the sodium lamp and find the region of maximum fringe contrast which is characteristic of the ZPD condition; third, use the white-light source and a green filter—the narrow bandwidth of the filter widens the coherence length of the interfering light; finally, carefully scan the range of good green-light fringe contrast to find the white-light fringes, which are present within only a *few microns* of the ZPD condition.

Proceed as follows:

Step 1: Find straight laser fringes

You now need to use the camera lens to make a better image of the fringes. To correctly align the lens, it is helpful to use the laser spots rather than the image created by the diffuse light from the microscope objective.

Move the microscope objective to one side so that you see only the laser spot. Then move the viewing screen back from the beamsplitter so that it is 40–50 cm from the center of the beamsplitter and position it so that the spot hits the center of the cross.

Place the camera lens **between the beamsplitter and the viewing screen with the *front* of the lens pointing toward the beamsplitter and positioned so that there is about 5 cm between the lens base and beamsplitter base.** (See Fig. 3 to note the lens position.) Move the camera-lens base side-to-side and twist it about the center of the base to bring the optical axis of the lens along the line of the laser-light beam. This will be when there are no visible side spots on the screen and the main spot is centered on the cross.

The purpose of the lens is to bring into a real image the virtual fringes that cannot be projected onto a screen without it. The fringes produced by an interferometer are classified according to whether they are real or virtual (and whether they are localized or non-localized). In certain interferometers all types of fringes are present simultaneously; this is true with the Michelson interferometer as we have it configured. Real fringes are produced when the light source emanates (mostly) from a single point, as is the case for the laser light coming from the microscope objective. When the light source is extended over space, such as with the white light and sodium lamp, the lack of coherence from different regions of the source washes out the real (projectable) fringe pattern. With a lens, we can overcome much of this effect by focusing onto the screen the virtual *fringes of equal inclination*,

also called *Haidinger fringes* that are also present. See the references in Hecht for a fuller discussion of this point.

Return the microscope objective to its position **close** to the beamsplitter "Face A". You should see the fringe pattern again, but the light will be notably brighter. The fringes should be evenly illuminated.

Adjust the "V" and "H" screws on the fixed mirror and turn the micrometer knob so that you can clearly see a circular fringe pattern on the viewing screen. Then turn the "H" screw a small amount so that the center of the ring pattern is at or near the right edge of the fringe image. You should see a collection of circular arcs curving toward the right.

Turn the micrometer knob and note the effect on the curvature of the fringes. If the curvature increases, turn the knob the opposite way. At some point you will see the curvature *reverse direction*—the fringes will curve to the left rather than the right. Set the knob so that the fringes appear to be straight.

Finally, make small adjustments to the fixed mirror to make the fringes be vertical with about 5-6 fringes visible.

Step 2: Find sodium lamp fringes

Remove the microscope objective from its place and set it aside. (Leave the laser on; you may need it if you bump something out of alignment.) Place the sodium lamp assembly (with iris) so that front edge of the base is about 5 cm from the base of the beamsplitter. Open the iris to approximately 10-15 mm diameter. Adjust the position of the lamp so that the image is evenly illuminated on the screen. Be careful not to bump the beamsplitter platform or the mirrors when moving hardware around.

You should see vertical fringes on the screen, although they may not be as distinct as those from the laser. If you don't see *any* fringes, check to make sure that you haven't bumped a mirror or the beamsplitter by looking for laser fringes with the laser and microscope objective.

Assuming that you can now see some fringes with the sodium lamp, slowly turn the micrometer knob in one direction. If you are not too far from the ZPD point, you should see the fringe contrast decrease until the screen is nearly fringe-free, and then the fringes will sharpen up again. As you keep turning the knob, the fringe contrast will get sharper and fuzzier, but eventually blur out altogether.

Then turn the knob the other way, and note how each time the fringes pass through a high-contrast point they get more and more distinct until you pass through the point of maximum fringe contrast. If you keep going, the fringes will get progressively fuzzier, as before.

Find the setting of the micrometer knob where the fringes have the highest contrast. If you are lucky, it will be pretty close to where you started when you put the sodium lamp in place.

Finally, open the iris to the maximum and adjust the knob to give maximum contrast. The open iris makes the region over where you can see the fringes narrower, since it reduces the effective spatial coherence of the source. After you have found the point of maximum contrast, set the sodium lamp aside, but leave it turned on, since you will need it later.

Step 3: Find green fringes

Write down the setting of the micrometer knob that gives the strongest sodium-lamp fringe contrast. It is useful to have this setting on hand in case you move the knob too far in the adjustments below, and you will need it for your report (see below).

Place the white-light source in the beam path so that the front of the housing is approximately 25 cm from face "A" of the beamsplitter. Turn on the power for the white light source. The housing for the white-light source has its own iris. Open this iris to about 1 cm diameter. Move the lamp around so as to get the brightest, most symmetric disk of light on the viewing screen.

Caution: The white-light lamp housing gets very hot – avoid touching it.

Now place the green (546 nm) filter provided in its holder between the camera lens and the screen, but close enough to the lens that it intercepts all of the light from it. The green filter will increase the coherence length of the light and make it easier to locate the ZPD point.

Slowly turn the micrometer knob in one direction and watch for the appearance of green fringes. If you find the fringes try to maximize the contrast that you see. If you don't see any green fringes, set the micrometer knob back to where you started (you wrote this point down, right??), and then slowly turn the knob in the opposite direction.

Once you find the fringes, note how much you can move the knob before the fringe contrast barely begins to weaken—this will give you a sense of how far you can move the mirror when you look for the much narrower range of white-light fringes.

Set the knob to the point where you think the contrast is greatest.

Step 4: Find white light fringes

Remove the green filter and hunt for the white-light fringes. These fringes are visible over only a very small range of mirror positions (several microns), so considerable care is required to find them. When you do observe the rainbow-like white-light fringes, pause to admire their beauty, shout *eureka!*. Note the micrometer reading (black scale) at which the white-light fringe pattern is centered this is the ZPD position. Record this—you will need it later.

IF YOU DO NOT FIND THE FRINGES AFTER 5 OR 10 MINUTES OF EFFORT, ASK FOR HELP FROM A STAFF MEMBER. (The staff member will perform, quickly, steps 1 through 3 above. The usual problem is that something has been bumped, causing the alignment to be off.)

Once you have found the fringes, make them vertical (by adjusting the V knob) and adjust their separation (H knob) to achieve a suitable display (6-8 fringes) on the viewing screen. Now estimate the coherence length of the white light source by carrying out the following exercise:

Pick a spot on the viewing screen (the vertical center line is a good choice). Translate the movable mirror and note how the fringes move across the screen. Set the knob to position the pattern so that the fringe contrast at the reference point is about half as strong as it is at the center of the fringe pattern. Record the knob position. Then turn the knob to translate the pattern across the screen so that it is at the other position where the fringe contrast is about half what it is at the center and record the knob setting. Calculate the distance moved. Use this distance to calculate the coherence length of the source. Hint: study Fig. 1 and the related mathematics. Another hint: the mirror displacement is *not* equal to the change in path length, but it is related to it—how?

Confirm with the TA that you have found the white light fringes and made the mea-

surements necessary to calculate the coherence length of the source and carry out the exercises described below. The TA will sign your data sheet for this part at this time.

For your report: Describe the appearance of the white light fringes in your report. What kind of symmetry is there in the fringe pattern? Why is there a rainbow effect?

You should have the micrometer setting for maximum fringe contrast with the sodium lamp and the micrometer setting for maximum fringe contrast with the white light in your data. Compare these settings and comment on any differences.

Show the calculations and reasoning behind your derivation of the coherence length of the white light. Compare your value with that given by Hecht (Table 7.1, p. 318, 5th edition).

2 Michelson Interferometer as a Fourier Spectrometer: Sodium Yellow Lines

The two yellow lines in the sodium spectrum have wavelengths $\lambda_1 = 588.995$ nm and $\lambda_2 = 589.592$ nm ($\Delta\sigma = 17.192$ cm^{-1}). Using observations of the fringe contrast as a function of path the difference Δ, you will experimentally determine this wavelength difference and make an approximate determination of the Gaussian envelope of the fringe contrast.

The fringe contrast is observed with a linear CCD (charge coupled device) array. This array consists of 1024 elements called pixels. The pixels are .5 mm high and are arrayed along a line with a separation of 25 microns between the centers of adjacent pixels. The overall length of the array is just over 2.5 cm.

The output of the array controller is a series of 1024 voltages, with each voltage level being proportional to the intensity of the light falling on that particular pixel. The output is conveniently viewed on an oscilloscope.

Start with the mirror at the ZPD position. Turn off the white light source and move it aside **(careful – the lamp housing is very hot)**. Move the sodium lamp back into its previous position so as to obtain a fringe pattern on the viewing screen. Adjust the position of the lamp and iris to obtain the clearest fringe pattern. Adjust the vertical and horizontal adjust screws on the fixed mirror so that you see 6-8 dark vertical fringes on the viewing screen.

Turn on the power to the Linear CCD (charge coupled device) Readout System and press the RESET switch so that the green LED labeled ACQ (ACQuire) is on. Turn on the scope. Position the CCD array housing so that the array housing (tan perforated board) is about 17 cm from the end of the lens barrel. You should see a readout of the fringe pattern intensity on the scope that looks something like that in Fig. 4. To get a nice centered pattern of reasonable scale on the scope screen, it may be necessary to adjust the array position by sliding the carriage along the rail (loosen clamping screw on back side first) and/or adjust the vertical sensitivity on the scope. Note: the linear array is very sensitive to background light, so make sure all the overhead lights are off when viewing the array output. If the array output disappears at some point during your measurements, press the RESET switch.

With the movable mirror in the ZPD position, the fringe contrast will be close to maximum. Positions of maximum fringe contrast are called an antinodes. **The fringe contrast for a given mirror position is taken to be the maximum peak-to-peak voltage of the displayed waveform, as shown in Fig. 4.** This voltage difference represents the intensity difference between

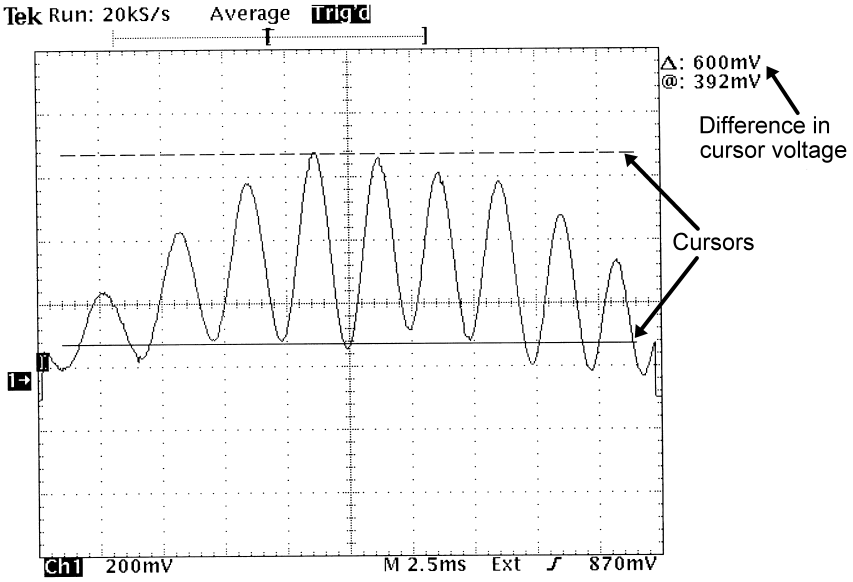

Figure 4: Measurement of the peak-to-peak voltage created by fringes from the sodium lamp. This screen grab was taken with the mirrors near zero path difference. Note that the peak-to-peak voltage is found by using the horizontal cursors, and then reading the difference between them with the "Δ" indicator near the top right of the screen.

a bright fringe and a dark fringe. Move the mirror in either direction from ZPD and observe that the fringe contrast decreases until it almost disappears—the waveform display shows a relatively smooth line, and the area near the CCD detector looks uniformly illuminated. The position of minimum fringe contrast is called a node. The fringe contrast does not disappear completely because the two sodium lines are not of equal intensity.

Now find the first 6 positions of minimum fringe contrast (nodes) on both sides of the ZPD position (12 positions total). By translating the movable mirror back and forth through the node, you can get a good feel for the position of the node.

Number the positions of the nodes consecutively and record the position in mm vs. node number. It is a good idea to make a quick plot as you go; graph paper is available in the lab. What do the consecutive numbers represent? As the path length difference changes from one position of minimum contrast to the next, the number of wavelengths of the longer wavelength sodium line along the additional path length difference changes by an integer n and the number of wavelengths of the shorter wavelength line increases by $n + 1$.

For your report: From a plot of node position vs. node number derive a value for the spacing between successive nodes. From this spacing, determine the splitting in nanometers between the two sodium D lines. Compare your result to the accepted values given at the beginning of this section.

Now find the approximate Gaussian envelope of the fringe contrast by measuring the fringe contrast at the position of the antinodes. Start by returning the movable mirror to the ZPD position, and adjust it to give the maximum peak-to-peak amplitude as seen on the oscilloscope display. Measure and record the maximum peak-to-peak amplitude of the signal displayed on the scope. Note that you can use the cursor function of the scope to help you out, as indicated in Fig. 4.

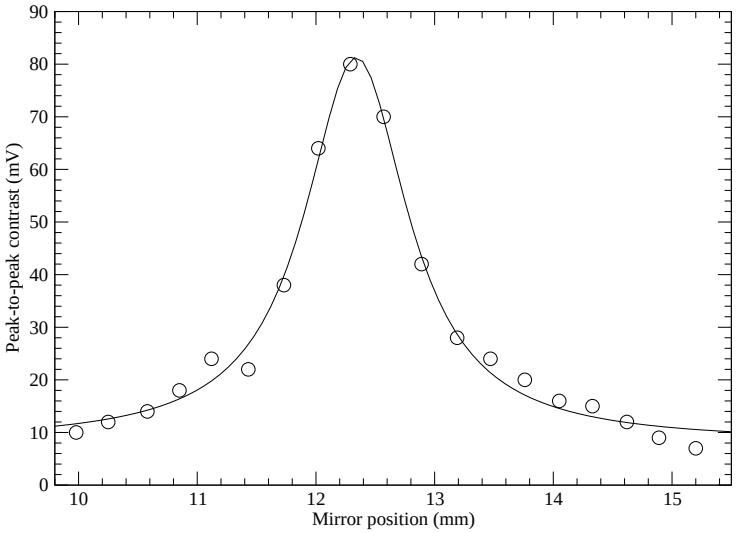

Figure 5: Typical data from the fringe contrast measurement of the sodium D lines. The line is a fit to a Lorentzian lineshape. Your data may appear somewhat different in both amplitude and lineshape, since the measurement is sensitive to the iris opening, the type of lamp, and the positions of the optical components.

Displace the mirror a distance equal to the spacing between the nodes you found above and again measure the contrast. Repeat the measurement for as many antinodes on either side of the ZPD position that you can reasonably measure (6 is typical, more is better). It can be difficult to find the best mirror position to measure the antinode by direct adjustment. You may find it easier to calculate the "average" of the two node positions on either side of the antinode you want, and just park the mirror at that "average" location. For example, the antinode between node positions x_n and x_{n+1} will be located at $(x_n + x_{n+1})/2$.

As the distance from the ZPD position increases, the observed fringe pattern becomes less symmetric and it is more difficult to determine the maximum peak-to-peak voltage (see Fig. 5). Don't worry—this is due to the inherent properties of the fringe pattern, and you can see this by putting the viewing screen back in front of the linear array. At ZPD the fringes appear nearly straight, but as you translate the mirror to one side of ZPD, the fringes become curved in one direction, and as you translate the mirror to the opposite side of ZPD, they become curved in the opposite direction. This curvature and change in fringe spacing across the pattern result in the non-symmetric displays, and the resulting difficulty in determining the fringe contrast allows one to get only an approximation of the Gaussian envelope.

For your report: After taking the fringe contrast measurements, plot them as a function of the position of the movable mirror and see that the outline resembles a Gaussian. Taking zero as an approximation to the baseline for the Gaussian, use a ruler to measure the FWHM, and divide by 2 to get $\Delta_{1/2}$. Use this number to find $\delta\sigma$. Compare this value to the value for a Doppler broadened source,

$$\delta\sigma_D = 2\sigma_0\sqrt{\frac{2kT\ln(2)}{Mc^2}}\ , \tag{5}$$

where k is Boltzmann's constant and M is the mass of the sodium atom. Assume the temperature T to be 600° Kelvin.

You will find that $\delta\sigma$ derived from your measurements is much larger than the Doppler broadening, $\delta\sigma_D$. This is typical of gas-discharge lamps like the one used in this experiment. Special, low-pressure lamps can achieve much smaller values of $\delta\sigma$, with corresponding values of $\Delta_{1/2}$ approaching 1 meter.

For your report: Calculate the coherence length of the sodium lamp emission from the FWHM of your measured peak. Compare this number to what you found for the white light, and if you measured it, the white light sent through the green filter.

Shut Down

When you have completed your measurements, please turn off all light sources, all electronics, and put the plastic covers on the various optical components.

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