THE MICHELSON INTERFEROMETER

Intermediate (first part) to Advanced (latter parts)

Goal: There is a progression of goals for this experiment but you do not have to do the last goal. The first goal is to align the interferometer and calibrate it. Calibration should be done both mechanically and optically with a HeNe laser. The second goal is a study of the sodium doublet. One measures the average wavelength of the two lines and the separation of the lines. The final experimental goal is to find interference fringes for white light and measure it's coherence length.

Introduction:

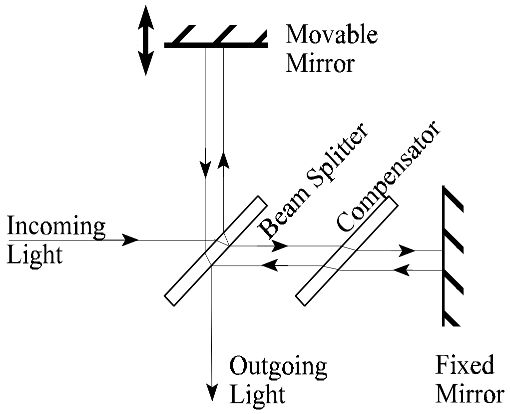

Figure 1 The optics of the Michelson Interferometer. Note the light directed away from the mirrors is offset from the light directed toward the mirrors for clarity

Note: The observation of fringes associated with the sodium doublet is a rather difficult experiment and the observation of white light fringes is even more difficult. Understanding how the concept of coherence length relates to this experiment is almost essential to complete these goals.

Reading:

ADC
Michelson program writeup
Stepper motors

Good optics text
Fourier transforms and FFT

Homework:

1. Indicate how the standard michelson interferometer optics is the same as the optics shown in fig. 2.

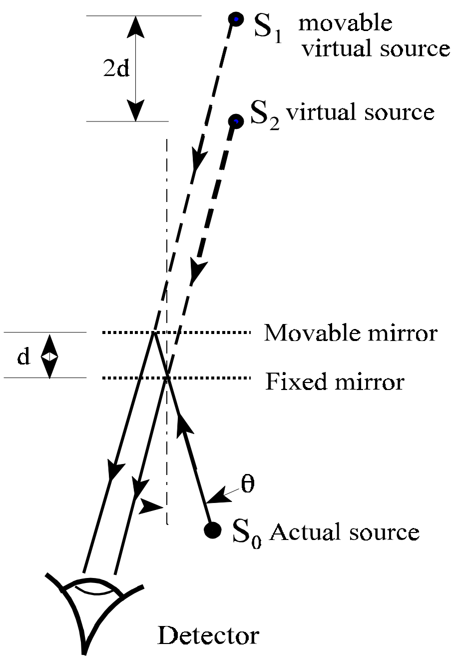

Figure 2 The optics of the Michelson Interferometer is equivalent to the that of two sources S_1 ans S_2, that are emitting light that is in phase. Note: source S_1 is movable.

2. Explain changes the optics in fig.1 and 2 required to account for the finite size of the light source

3. For the optics shown in fig.2, at what distance should the detector (eye) be focused?

4. What would the effect if the two mirrors in fig.1 were not perpendicular or the two mirrors in fig. 2 were not parallel? How is this like a wedge of air between two flat plates of glass?

5. Derive the condition for fringes in terms of the wavelength of light and the lengths of the two optical paths and the viewing angle θ.

6. Define coherence length and coherence time. What is the relationship between these quantities and the spread of optical frequencies under observation (for example the natural line width)?

7. What is the relationship between the coherence length and the mean lifetime of the upper state of the transition that produces the line?

8. What are the expected wavelengths for a HeNe Laser, for the sodium doublet and for white light.

9. How close to a single frequency does a laser produce? That is how narrow is the "line" produced by a laser?

10. In this experiment how close to equal are the two intensities from the two different paths?

11. In this experiment, how close to equal are the intensity associated with the two wavelength of the sodium doublet?

12. Why, as shown in Fig (1) is a compensator plate used?

13. What is the effect of changing the sampling rate?

Experimental tasks

There are three experimental tasks, but only the first two are required.

1. Calibrate the spectrometer's motion (that is nanometers per stepping motor step) using the HeNe laser and compare this with the mechanical calibration (that is from the gearing).
   Questions What is the size of a single step of the stepping motor. (Degrees of the motor shaft, degree on the threaded shaft, physical movement of the mirror in mm, nm , Å)

2. Measure the splitting of the sodium doublet.

3. Measure the coherence length of white light.

The third task is especially difficult, and requires skill, patience and luck. Even the second task with the sodium doublet will be quite challenging.

Procedure

The basic procedure is the same for each part in that the basic setup shown in Fig(1) is used, just with a different light source. For the first task the HeNe laser is used. For the second task, a sodium vapor lamp is used along with an interference filter.. A standard incandescent lamp is used for the last part.

Even when working with the other light sources, it is easier to align the optics using the laser. In all cases the angular orientation of the mirrors is shifted until the outgoing rays from the two mirrors overlap and the light rays interfere.

When working with the laser, no additional detection optics are needed, but for the other tasks a lens is needed to focus the light onto the detector. The lens should be place such that parallel rays are focused. In Fig (2) the two outgoing rays are parallel, and must be brought together (focused) to interfere.

The finite coherence length of the light emitted by the sodium and the incandescent lamps is one of the things that makes working with sources difficult. (Low light levels compared to background, low contrast, and the need for near perfect alignment are other difficulties.) Because of the short coherence length, the optical paths lengths that the light travels on both possible paths must be nearly equal. For the sodium source nearly equal means better than a millimeter, but for the white light source it is more like a few microns or at best tens of microns. For measuring the sodium, it is possible to be within a millimeter of equal path lengths and still see nothing, because one half of the doublet is canceling the other half (see historic recording of the sodium doublet above the windows).

Sodium Doublet:

The sodium light source takes a few minutes to warm up because in the cold state most of the sodium in the form of a solid. As the lamp warms up the sodium becomes a gas.

When working with the sodium light source an interference filter is used so that only light associated with the sodium doublet is transmitted to the interferometer. Without this filter, other lines emitted by sodium would interfere with the doublet lines.

Use the laser to make a preliminary alignment of the mirrors. Once this is done, put the sodium lamp in place. With the sodium lamp, it is safe to look into the interferometer. It turns out that when aligning the optics with the sodium lamp, using your eye as the detector is easier that using the photodetector or even forming the image on a screen. In part this is because, as discussed above, one needs to use a lens at the exit of the interferometer with the lens set to focus parallel rays from the interferometer onto the detector.

When working on the sodium doublet, it is important to adjust the mirrors until the central bull’s eye is found. In addition to the alignment of the mirrors, it is important to set the optical path length to as near as equal as possible. If you look at the historic plot of the sodium doublet you can see how the contrast decreases as the differences in the path lengths increase. You can also be just plain unlucky by initially setting the path lengths such that you are initially observing in a “dead spot” in the beat pattern. For this reason it is suggested that you slide the stepping motor back to disengage the worm gear, then you can quickly adjust the path length.

Varying the size of the aperture through which light from the sodium lamp passes may help improve contrast.

White Light:

Basically every trick and warning that was given with respect to the sodium doublet applies to working with white light only more so. The path length must be equal to within a few (or few dozen) wavelengths.

Theory:

One can start with the assumption that the electric field , E(x,t), associated with light is given by:

$$E(x,t) = E_{MAX}\sin(\omega t - \frac{2\pi}{\lambda}x - \phi) \ . \qquad \textbf{(1)}$$

Here x is the optical path length from the point source, t is the time, E_{MAX} is the maximum field, ω is the angular frequency, λ is the wavelength, and ϕ is the phase of the electric field at the source at t = 0. Recall the relationships between the period, T, the frequency, *f*, the angular frequency, ω, and the wavelength, λ:

$$\begin{aligned} f &= \frac{1}{T} \ , \\ \omega &= 2\pi f \ , \qquad \textbf{(2)} \\ f\lambda &= c \ . \end{aligned}$$

Interference occurs when two bits of light are at the same place at the same time. When detecting light, it is intensity, I, which is actually observed is the time average of the square of the sum of the individual electric fields. That is:

$$I \propto \left\langle \left(\sum E \right)^2 \right\rangle . \qquad \textbf{(3)}$$

To add the light that takes two different paths together one needs to recall the trig identity for adding sines:

$$\sin\alpha \pm \sin\beta = 2\sin\tfrac{1}{2}(\alpha \pm \beta)\ \cos\tfrac{1}{2}(\alpha \mp \beta) \ . \qquad \textbf{(4)}$$

If the source such as the laser that produces a single wavelength and *if* the two paths, the intensities of light are equal it is not that hard to add two rays of light of the form given by eq (1). Squaring this sum is straightforward and the last trick is to take the time average. In this case, taking the time average is integrating over one period.

In the case of the sodium doublet, the situation is more complex, in that there are two wavelength (and two frequencies and two periods) associated with each of the two paths. Thus you need to sum four terms like eq. (1). The time average must be taken by integrating over an integral number of periods associated with each wavelength.

Am. J. Phys., Vol. 58, No. 6, June 1990 Pages 580 - 581
Interference patterns from circularly polarized light using a Michelson interferometer
Walter Roy Mellen

Coherent light in the two arms of a Michelson interferometer are made circularly polarized but with opposite rotations. When the two beams recombine, the light is linearly polarized but the direction of polarization changes depending on the phase between the two beams. When a linear polarizer is used on the output and rotated, the observed interference fringe pattern shifts. If the field of view contains circular fringes, the continuous rotation of the polarizer in one direction makes the circles continuously expand or contract.

Am. J. Phys. Vol. 64, No. 7, July 1996, Pages 928-934
Dominant color reversals and chromaticity cusps in interferometric color mixing
Thomas E. Kiess and Richard E. Berg

White light was injected into a Michelson interferometer to obtain color fringes, which show a succession of dominant colors that we have analyzed quantitatively. For a given interferometric path length difference, delta L, the resulting color fringe was sent to a diffraction grating spectrometer and light-sensitive detector, to record its spectral composition. This data enabled us to depict the color in the two-dimensional color space of the x-y C.I. E. chromaticity diagram. In this analysis, we show the dominant color in the progressioin of color fringes in interferometric color mixing to reverse the direction with which it sweeps through the visible spectrum, as delta L is monotonically increased. This phenomenon is represented by spiraling with cusps and reversals of curvature in the C.I.E. x-y plane. Our measurements agree favorably with a theoretical model showing cusp behavior. We show the cusps to signify a transition from in- to out-of-phase behavior in the relative growth of x and y. This result is robust, persisting for many trial spectral power distributions (SPDs) of the incident "white light" illuminant.

Am. J. Phys., Vol. 50, No. 5, May 1982 Pages 464 - 465
Properly used "aliasing" can give better resolution from fewer points in Fourier transform spectroscopy
Y. D'Astous
M. Blanchard

In the past years, the Journal has published a number of articles[sup 1-5] devoted to the introduction of Fourier transform spectroscopy in the undergraduate labs. In most papers, the proposed experimental setup consists of a Michelson interferometer, a light source, a light detector, and a chart recorder. The student uses this setup to record an interferogram which is then Fourier transformed to obtain the spectrogram of the light source. Although attempts have been made to ease the task of performing the required Fourier transform,[sup 6] the use of computers and Cooley-Tukey's fast Fourier transform (FFT) algorithm[sup 7] is by far the simplest method to use. However, to be able to use FFT, one has to get a number of samples of the interferogram, a tedious job which should be kept to a minimum. (AIP)

Am. J. Phys., Vol. 45, No. 2, February 1977 Pages 166 - 169
Visible spectroscopic studies with Fourier transform interferometry
Jeffrey Davis
Timothy M. Rynne

Use of a Michelson interferometer in studies of visible spectroscopy is presented. The experimental setup is discussed for obtaining reflectivity spectra of various semiconducting materials. The resulting interferograms are analyzed using a Tuckey-Cooley fast Fourier transform technique. Results include measurements of the absolute reflectivity of coated germanium, uncoated germanium, coated silicon, and the output spectra of both red and green light-emitting diodes.

Am. J. Phys., Vol. 40, No. 8, August 1972 Pages 1070 - 1078
Fourier Transform Spectroscopy Using a Michelson Interferometer
J. C. Albergotti

The use of the Michelson interferometer as a Fourier transform spectrometer is described. Fringe visibility curves are obtained with an electron photomultiplier or silicon photocell, and Fourier transforms of the visibility curves are taken with the aid of a digital computer. Application of the technique is made to the axial mole structure and phenomenon of "hole burning" in He_Ne lasers, to the shape of the mercury green line and sodium yellow lines and to the Zeeman spectrum of the mercury green line Delta m[sub j]=0 transitions.

Am. J. Phys., Vol. 40, No. 4, April 1972 Pages 629 - 630
Modifications of Apparatus for Fringe Visibility with a Michelson Interferometer
Wallace A. Hilton

Am. J. Phys., Vol. 43, No. 2, February 1975 Pages 180 - 180
Fourier-transform spectroscopy using any old Michelson interferometer
R. G. Layton
J. K. Brower

Am. J. Phys., Vol. 38, No. 12 December 1970 Pages 1390 - 1395
White light fringes obtained with the Michelson interferometer
P.A. Young
D.E. O'Conner

Circular white light fringes are seen when a dispersing medium is placed in one arm of a Michelson interferometer. A formula for the number of fringes as a function of the bandwidth of the source and the dispersion of the medium is obtained which agrees well with experiment. The phenomenon has been made into a student experiment on wave groups.
