

Experiment 4

The Michelson Interferometer

1 Introduction

There are, in general, a number of types of optical instruments that produce optical interference. These instruments are grouped under the generic name of interferometers. The Michelson interferometer causes interference by splitting a beam of light into two parts. Each part is made to travel a different path and brought back together where they interfere according to their path length difference.

You will use the Michelson interferometer to observe the interference of two light sources: a HeNe laser and a sodium lamp. You will study interference patterns quantitatively to determine the wavelengths and splitting of the Na D lines empirically. You will use the HeNe laser interference spectrum to calibrate the interferometer.

2 Background - see Hecht, Chap. 9, Pedrotti Chap. 7 and 8

2.1 The Michelson Interferometer

The Michelson interferometer is a device that produces interference between two beams of light. A diagram of the apparatus is shown in Fig. 1. The basic operation of the interferometer is as follows. Light from a light source is split into two parts. One part of the light travels a different path length than the other. After traversing these different path lengths, the two parts of the light are brought together to interfere with each other. The interference pattern can be seen on a screen.

Light from the source strikes the beam splitter (designated by S). The beam splitter allows 50% of the radiation to be transmitted to the translatable mirror M_1 . The other 50% of the radiation is reflected to

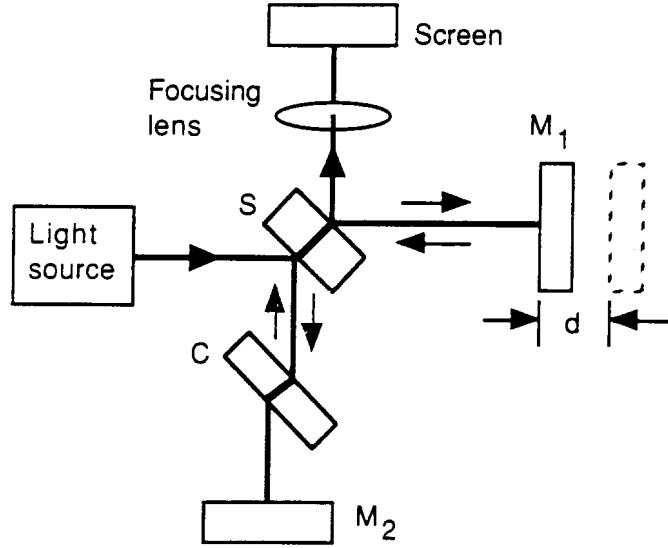


Figure 1: Schematic illustration of a Michelson interferometer.

the fixed mirror M_2 . The compensator plate C is introduced along this path to make each path have the same optical path length when M_1 and M_2 are the same distance from the beam splitter. After returning from M_1 , 50% of the light is reflected toward the frosted glass screen. Likewise, 50% of the light returning from M_2 is transmitted to the glass screen. At the screen, the two beams are superposed and one can observe the interference between them.

2.2 Interference of Waves With a Single Frequency

If two waves simultaneously propagate through the same region of space, the resultant electric field at any point in that region is the vector sum of the electric field of each wave. This is the principle of superposition. (We assume all waves have the same polarization).

If two beams emanate from a common source, but travel over two different paths to a detector, the field at the detector will be determined by the optical path difference, which we will denote by $\Delta x = x_2 - x_1$. A related quantity is the phase difference, $\Delta\phi$, given by

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta x = k\Delta x, \quad (1)$$

where k is the wavenumber. Constructive interference occurs when

$$\Delta\phi = 2m\pi, \quad m = 0, \pm 1, \pm 2, \pm 3, \dots \quad (2)$$

Destructive interference occurs when

$$\Delta\phi = \pm(2m + 1)\pi, \quad m = 0, 1, 2, 3, \dots \quad (3)$$

2.3 Fringe Visibility for Interferograms Made With Two Frequencies

We will now consider the case of two frequencies with numbers k_1 and k_2 that together follow two different paths with a common path difference of Δx . The two frequencies cannot show interference for times longer than their periods. Thus each frequency produces its own two beam interference intensity pattern:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta$$

and

$$I' = I'_1 + I'_2 + 2\sqrt{I'_1 I'_2} \cos \delta'$$

with $\delta = k_1 \Delta x$ and $\delta' = k_2 \Delta x$ being the corresponding phase differences for the two beam paths. Both frequency light beams travel the same paths and have the same path difference Δx . Write the ratio $I_1 / I_2 = I'_1 / I'_2 = r$ because the beam splitter ratio is the same for both frequencies and the intensity ratio for the two frequencies as $I'_1 / I_1 = a$. Then the total intensity is given by:

$$I_T = I_1(1+r)(1+a) + 2I_1\sqrt{r}(\cos \delta + a \cos \delta'). \quad (5)$$

The first term is the average intensity and the second term with the two cosine functions is the sum of the two interference terms. The interference terms don't simplify much further but the dominant behavior for $a \ll 1$ has the dependence on δ and δ' of the form

$$2 \cos\left(\frac{\delta + \delta'}{2}\right) \cos\left(\frac{\delta - \delta'}{2}\right) = 2 \cos\left(\left(\frac{k_1 + k_2}{2}\right)\Delta x\right) \cos\left(\left(\frac{k_1 - k_2}{2}\right)\Delta x\right).$$

This product of cosines shows a fast oscillation at the mean wavenumber frequency and a slow envelope at the wavenumber difference frequency. An example plot of Eq. (5) is shown in Figure 2 for the case $I_1 = 1$, $r = 0.7$ and $a = 0.8$.

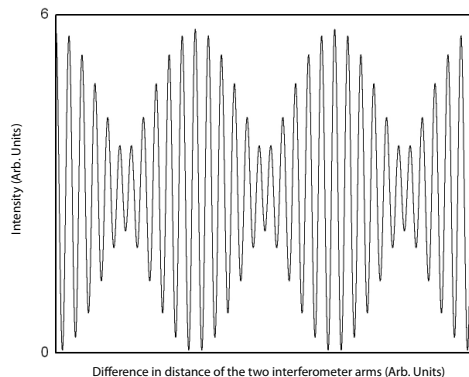


Figure 2: Intensity beat signal from two input frequencies into a Michelson interferometer. The function shown is for the case $I_1 = 1$, $r = 0.7$ and $a = 0.8$.

3 Experiment

In the following experiments, you will calibrate the movement of M_1 with the HeNe laser and use the interferometer to accurately measure the wavelengths of the fine structure doublet of the sodium D line, a consequence of the spin of the electron.

3.1 Calibration with HeNe Laser Light

Inject the laser beam into the Michelson interferometer. Make sure the beam is properly retro-reflected. Initially, you will see two bright spots on the screen. Adjust the angle of the fixed mirror until these two spots overlap. You can use lenses to expand the beam if necessary.

Note, take care when moving M_2 as the interference is very sensitive to its alignment. As you translate mirror M_1 , you will see fringes appearing and disappearing on the screen. The interferometer lever arm reduction factor is 5X, so that the wavelength of the light can be found using

$$\lambda = \frac{1}{5} \left(\frac{2d}{m} \right) \quad (4)$$

where d is the distance the micrometer moves and m is the number of rings that disappeared (or appeared) while mirror M_1 moves. Note that for a given d , M_1 moves $d/5$. Use the synchronous motor to facilitate the turning of the micrometer. As the micrometer is turning, record the interference data with the computer. The motor runs at 0.5 rpm and the micrometer moves 5×10^{-4} m/rev. This can give you a check of things, but we will use the HeNe data (look up the HeNe wavelength on the web) to accurately calibrate the speed.

3.2 Sodium Light

Now use the sodium lamp to produce an interference pattern. Since the spectrum of this light consists primarily of two closely spaced lines (a doublet), each wavelength will produce its own set of fringes. Your goal will be to empirically determine λ_1 and λ_2 by measuring the finely spaced fringes and the beat pattern.

It is *much* more challenging to get good interference patterns with the lamps, so take your time and play with alignment, lamp placement, and possible lens placement. You will need to increase the gain in your detection system.

You should observe both the finely spaced pattern as well as a modulation in the contrast at the difference frequency of the two lines. Your goal is to as accurately as possible measure the wavelength of the two sodium lines. Be sure to carefully estimate uncertainties.

Each of the doublet lines of the sodium lamp are not monochromatic

due to broadening from pressure effects and motion of the atoms in the lamp (Doppler effect). This means the *coherence length* is not that large. If the path length difference is too large, you will not see any fringes. Measure the coherence length of your lamp.

Modified by R. G. and L. A. O. March 31, 2008