Calibration and Use of a Michelson-Morley Interferometer

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INTRODUCTION

Einstein’s theory of special relativity started a revolution for physics during the early twentieth century. One of the major arguments for his theory is the idea that the speed of light is an invariant in all reference frames. This idea that the speed of light is not affected by one’s frame of reference changed the way that scientists would treat light. This new idea that Einstein theorized completely challenged classical physics and started a new generation of scientific discoveries. Such a simple theory introduced by Einstein, but where did it come from? His postulates were made after he described the Michelson-Morley experiment, conducted a few years prior.

The Michelson-Morley experiment was a simple apparatus designed to show that light travelled through a medium called the Ether. Using classical physics, this assumption is intuitive—a particle or wave must have a medium (Ether) to propagate through. This experiment would use a device, called an interferometer, to detect Ether. To do this, the device would split a beam of monochromatic light into two paths, which are perpendicular to each other, before refocusing them on one spot. The interference pattern generated by the supposed slight path differences would be dependent on each beam’s reference frame. The two scientists theorized that when the interferometer is rotated 90 degrees, the interference pattern should undergo a phase change. This phase change would be due to light leaving the Earth’s frame of reference—using Galilean Transformations, the speed of light would decrease because it would no longer be moving along the same path as the Earth. What they found, however, is that the interference pattern does not change. They were not able to explain the null result that they received—it was not until Einstein’s proposal of his theory of special relativity that the experiment was explained and understood.[1]

The objective of this experiment is to become acquainted with a Michelson-Morley interferometer, and to gain experience in experimentation. In the experiment, the wavelength of a laser was determined by shining the laser through the interferometer. By varying the distance the light had to travel and observing the change in the interference pattern projected from the interferometer, the wavelength can be determined. The value calculated came out to be 552 nanometers, which is 12.8% off the theoretical value of 633 nanometers. Error in this experiment can be found in the design of the actual device, as well as from the unavoidable ‘noise,’ or vibrations present in the space around the device.

Theory

In this experiment, the interferometer is used to calculate the wavelength of the laser being shone through it. Moving one mirror farther away from the beam splitter results in a fringe change that can be observed in the image. By observing the fringe change of the interference pattern, the wavelength of the laser can be deduced according to the following equation:

$$\mathrm{m}\lambda = 2\mathrm{d} \qquad \text{(eq. 1)}$$

Where d is the change in distance that the mirror undergoes, and m is the number of fringe changes that appear on the screen.[2] To find a precise value for d, a few calculations must be made. The device being used has one special modification that allows this calculation to be used. On the side of the two-piece interferometer, there is a micrometer attached. This micrometer rests on a pivoting arm, some distance R from a rod that pivots it. This rod, when turned by the micrometer, uses friction to slide the interferometer some distance d away from the beam splitter. By relating the angular displacement to the circumferential displacement of the rod, the distance that the interferometer piece moves can be deduced. The relationship used is shown below:

$$\frac{\Delta \mathrm{C}}{\Delta\theta} = \frac{\mathrm{C_{total}}}{\theta_{\mathrm{total}}} \qquad \text{(eq. 2)}$$

With this, the desired d value can be calculated and then used to find the wavelength of the light. The value found could then be compared to the theoretical value using the percent discrepancy equation shown below:

$$\%\ \text{error} = \frac{|\text{actual} - \text{found}|}{\text{actual}} * 100$$

METHODS & MATERIALS

In order to measure the wavelength of the 633 nm laser being shone through the interferometer, the device first had to be calibrated. To do this, the interferometer had to be placed on top of the rubber mat to help suppress ambient vibration, which would generate ‘noise’ in the data. Then, the 633 nm laser and convex lens were placed so that they were in line with the beam splitter. With the laser turned on, the mirrors were both adjusted so that the two resultant beams both overlapped perfectly. This was done by shining the beams on a wall roughly five meters away from the device (the farther the surface, the more precise the calibration) and checking for a perfect overlap. When the two beams are aligned, the device is calibrated and can be used accurately. A white screen was then placed close to the device to clearly display the interference patterns generated from the two beams conjoining. If the circular interference patterns are not centered, the laser source can be slightly moved to place the focus of the projected light over the center of the interference pattern.

With the device calibrated and ready for use, the data can then be taken. On the micrometer attached to the interferometer, there are 10 ‘notches’ present on the side. Each notch represents one full turn of the micrometer. When the micrometer is turned, mirror 2 on the interferometer (See Figures 1 and 2) will move to the right. This change in distance (the d represented in Equation 1) changes the fringe pattern projected onto the screen—the circular fringes will move to the center and appear to disappear. Each fringe change was recorded for each notch on the micrometer. With ten notches total, the average of fringe changes was taken for the notches, and that value was used as the m value in the first equation. The values calculated represented some error due to the nature of the micrometer’s contact with the interferometer; however, the values yielded a result close to an acceptable and anticipated value of ten percent error. When the m and d values were known, the wavelength of light could then be calculated.

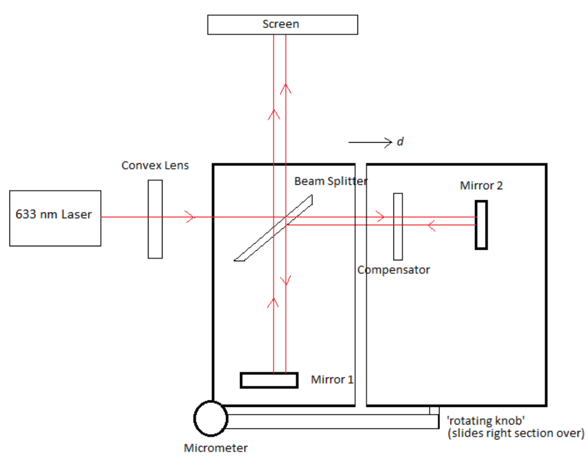

Figure 1: Side View of Micrometer

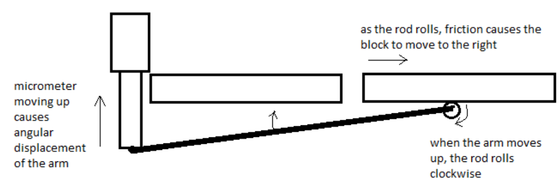

Figure 2: Diagram of the Interferometer

DATA & ANALYSIS

Micrometer notch:	fringes:
1	202
2	182
3	184
4	181
5	181
6	178
7	179
8	164
9	161
10	151
Average:	176.3

The above table depicts the collected data from the experiment. The 'fringes' column represents the number of times the fringes disappeared. The 'micrometer notch' represents the notch value, or number of turns at that data point. The average value here is the desired m value for Equation 1. The calculation conducted (and the error associated with the final value) to find the wavelength of the laser is shown below.

First, the angular displacement must be found. The arc length formula can be used to find this value. With a ruler, the length of the arm (R) was found to be 13 centimeters. The arc length (S) is the vertical displacement caused by the micrometer's movement and equals 0.254 centimeters. Because the angular displacement is so small, the 'arc' can be described by the linear movement of the micrometer.

$$S = R * \theta$$

$$\theta = \frac{S}{R} = \frac{0.254\text{ cm}}{13\text{ cm}} = 0.0195\text{ radians}$$

The circumference of the rotating rod must also be found so that the angular displacement and circumferential displacement can be related to each other.

$$C = 2\pi r$$

$$C = 2\pi(0.25\text{ cm}) = 1.57\text{ centimeters}$$

Now, equation 2 can be implemented to find the d value, or horizontal displacement of the second mirror on the interferometer.

$$\frac{\Delta X}{\Delta\theta} = \frac{X_{total}}{\theta_{total}}$$

$$\Delta X = \left(\frac{X_{total}}{\theta_{total}}\right)(\Delta\theta) = \left(\frac{1.57\text{ rads}}{2\pi\text{ rads}}\right)(0.0195\text{ cm})$$

$$\Delta X = 0.00487\text{ centimeters}$$

With this d value and the average m value found, the wavelength of the laser can be found using Eq. 1.

$$m\lambda = 2d$$

$$\lambda = \frac{2d}{m}$$

$$\lambda = \frac{2(0.00487\text{ cm})}{(176.3)} = 5.52 * 10^{-5}\text{ centimeters}$$

Finally, convert the answer to nanometers using stoichiometry and compare it to the correct value of 633 nanometers using percent discrepancy.

$$\left(\frac{5.52 * 10^{-5}\text{ cm}}{1}\right)\left(\frac{1\text{ m}}{10^{2}\text{ cm}}\right)\left(\frac{1\text{ nm}}{10^{-9}\text{ m}}\right) = 552\ \mathbf{nm}$$

$$\%\text{ error} = \frac{|633 - 552|}{633} * 100 = 12.8\ \%$$

DISCUSSION

As the above calculation shows, this experiment contains a high amount of error; however, this error was anticipated, due to the design of this interferometer. The contact between the rotating rod and the interferometer's moving plate is not perfect, so there is some amount of 'slipping' between the rod and the plate. This means that the micrometer is turning with no resulting fringe change. This will result in error. In addition to the slipping aspect of the rotating rod, another significant flaw in the design is found in the micrometer setup. Because the contact between the micrometer and the rotating arm is dependent on a stretched spring, holding the arm against the micrometer, a noticeable problem arises. When a string is stretched, the force in the spring is not linear—during the first few turns, the force being applied to the rotating rod was higher, causing more frictional force to be applied to the rod and plate. Close to the end, less force was applied which consequently had the opposite effect. To make a visual aide to describe the error in this experiment, a graph of the raw data in figure 3 was made in GNUplot:[3]

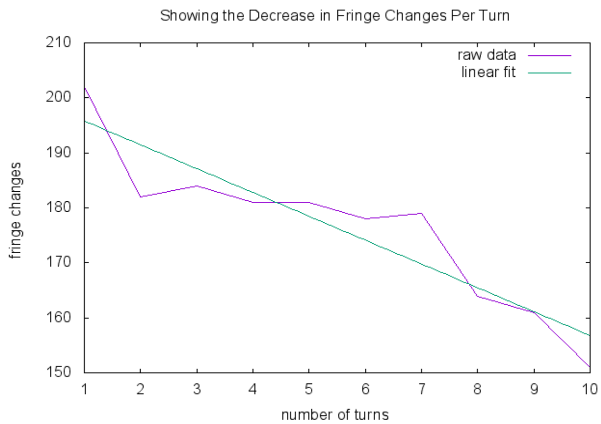

Figure 4: This Graph Shows the Decrease in Fringe Changes per Micrometer Turn

The green fit line represents how the spring contributed less force to the rotating rod, giving a constant decrease in fringe changes. The random, non-linear jumps in the raw data could possibly represent the slipping of the rod against the moving plate. This random slipping between the plate and the rod would contribute random error to the experiment.

CONCLUSION

The objective of this experiment was to become acquainted with the Michelson-Morley interferometer, and to also show some ability to conduct an experiment without the level of guidance and instruction in previous laboratory experiments. To do this, the Michelson-Morley interferometer was used to measure the wavelength of a laser being shined through it. By finding the average fringe change per micrometer turn and the horizontal displacement of the second mirror on the interferometer, the wavelength of the laser was calculated with Eq. 1. The value calculated is 552 nanometers, which is 12.8% off from the theoretical value of 633 nanometers.

The error in this experiment is mostly due to the design of the interferometer. If I could redesign the device, I would make a few changes to the micrometer and rotating rod setup. First, I would find some contact material with a higher coefficient of friction so that there is a better contact between the rod and plate. I would consider materials like rubber-to-rubber contact, instead of metal-to-metal contact. Rubber has a much better ability to grip onto objects, which would decrease in the slipping aspect of the device. Second, I would try to change the way the force of the micrometer is transferred to the moving plate. Instead of using the variable-force generated from the spring to rotate the small rod, I would make the force of the micrometer go in the same direction of the moving plate. I would create a simpler device as shown below:

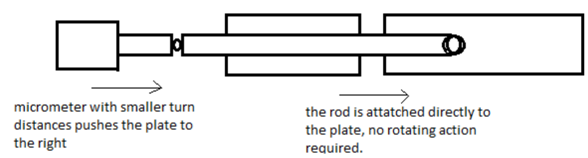

Figure 3: A Conceptual Representation of my Redesign of the Interferometer

These corrections would reduce most of the systematic error in the experiment. The only random error in this experiment can be found in the presence of outside noise. No matter how isolated this experiment is, there will always be some form of noise present; however, the amount of outside noise can be reduced. In the classic Michelson-Morley experiment, this noise was reduced by placing the interferometer on a granite slab that floated on a pool of mercury. In this experiment, a more effective method than a rubber mat can be used.

REFERENCES

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