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The Michelson Interferometer as a Device for Measuring the Wavelength of a Helium-Neon Laser

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Abstract: Interferometry describes the technique of analyzing interference patterns of waves to obtain information about their properties. The Michelson Interferometer is an instrument of interferometry that studies the interference pattern of a divided and subsequently recombined light wave. In this experiment, a Michelson Interferometer was used to determine the wavelength of a 5-milliwatt Helium-Neon laser. The average wavelength of four trials was measured to be 635 ± 28 nanometers (nm), with a standard deviation of 10 nm. This is compared to a literature value of 632.8 nm.
**Introduction:** The first Michelson Interferometer, assembled by Albert Michelson and Edward Morley, was used for the famous Michelson-Morley experiment. The purpose of this experiment was to prove the existence of ether, the mysterious medium through which light was theorized to propagate. While Michelson and Morley were unsuccessful in finding evidence for the non-existent ether, the apparatus they left behind is vastly applicable and provides a simple and effective method of determining, among other things, the wavelength of a laser beam. In this experiment, a red Helium-Neon (He-Ne) laser beam of known wavelength served as the light source for the Michelson Interferometer in order to demonstrate the capability of the interferometer to measure wavelength and to confirm the accepted wavelength of the laser.

**Theoretical Description:** The Michelson Interferometer is a common tool of interferometry. Interferometry is the technique of studying the interference of waves in order to determine particular characteristics of and relationships between the waves. Two special cases of interference are of particular interest: constructive and destructive interference.

Constructive interference occurs when the crest of one wave meets the crest of the other wave. If these are light waves, constructive interference corresponds with maximum intensity and thus the brightest resultant wave. Destructive interference occurs when the crest of one wave meets the trough of the other wave, and the resultant wave has an amplitude and intensity of zero. If these are light waves, a dark spot results.

It can be shown, by expressing the waves' amplitudes and intensities in terms of cosines and utilizing the standard definition of the wave number $k$, that the criteria for constructive interference of two waves is a difference in path-length, $\Delta d$, between the two waves of:

$$\Delta d = \frac{m\lambda}{2}, \quad m = 0, 1, 2...$$

where $m$ is any integer and $\lambda$ is the wavelength of the light.

One can also show that the criteria for destructive interference is a difference in pathlength of:

$$\Delta d = \frac{(m+\frac{1}{2})\lambda}{2}, \quad m = 0, 1, 2...$$

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**Figure 1: The bulls-eye interference pattern.** The interference pattern of concentric rings (See sketch at left) is created via the constructive and destructive interference of light waves. This pattern can be achieved and projected onto a viewing screen with the Michelson Interferometer.
A Michelson Interferometer allows one to observe the visible effects of constructive and destructive interference. It does so by dividing a beam of light into two beams of equal intensity, reflecting the beams via mirrors, and recombining the beams to produce an interference pattern like the sketch provided in Figure 1. The interference pattern can be, but is not necessarily, a “bulls-eye” pattern; this experiment studied such a pattern. The rings of the bulls-eye, which are referred to as “fringes,” are created by the constructive and destructive interference of the waves.

One can use the interferometer to change the path-length difference between the interfering waves. This will result in a change in the interference pattern – the concentric rings of the bulls-eye will move inward or outward, seeming to appear or disappear, as the path-length difference is altered. Given that constructive interference, represented by a bright fringe, occurs at integer multiples of the wavelength, one can count the number of fringes, $N$, that move as the path-length is changed and conclude that this must be the same number as $m$. That is, if $m = N$,

$$\Delta d = \frac{N\lambda}{2}, \quad N = 0, 1, 2...$$

which can be rearranged to yield:

$$\lambda = \frac{2\Delta d}{N}$$

In a Michelson Interferometer, the difference in pathlength is accomplished via adjustment of a mirror from which a beam reflects. As the path-length of one beam (called the “reference beam”) remains unchanged, and the path-length of the other beam (called the “sample beam”) is changed by a distance of $\Delta d$, the interference pattern is monitored concurrently to determine the number of fringes, $N$, that appear or disappear. With just these two pieces of information, one can determine the wavelength of the light.

*5 mw He-Ne laser*

Figure 2: Diagram of a Michelson Interferometer. A diagram of a typical Michelson Interferometer apparatus, including a diverging lens.

* laser was supported by two jacks
Apparatus Description: The elements of a Michelson Interferometer include: a light source, a beam splitter and compensating plate, a fixed mirror and a moving mirror (as well as knobs to adjust each), and a viewing screen onto which the interference pattern is projected.

Our setup, a schematic of which is provided in Figure 2, included a few more components. Because the optical components of the interferometer rest on a platform, our laser, a 5-milliwatt (mw) He-Ne laser, was elevated with two jacks. The entire system was supported by an optical bench. To ensure that the laser beam was approximately parallel to the surface of the optical bench, a level placed between the two jacks was utilized during setup. In order to magnify the beam and increase the size of the interference pattern to aid in counting the moving fringes, a -22-millimeter (mm) concave (diverging) lens was placed in front of the laser.4 If using a lens, it is important to ensure the laser beam passes through the approximate center of the lens.

After the laser passes through this lens, it encounters a beam splitter that must be oriented at 45 degrees to the incoming beam in order to evenly divide the beam into two beams of equal intensity. The front of the He-Ne laser was aligned with the edge of the jacks, which themselves were oriented to be as parallel to the interferometer as possible by using the grid of the optical bench for alignment.

The beam reflected by the beam splitter and subsequently reflected by the “moving mirror” passes through a glass plate preceding the beam splitter three times, and through the glass of the compensating plate exactly one time, before arriving at the viewing screen (See Figure 3). The beam that is transmitted through the beam splitter encounters the glass plate preceding the beam splitter just once, but passes through the glass of the compensating plate three times.

Figure 3: The path of light beams through the Michelson Interferometer beam splitter.

The figure above illustrates the laser beam as it hits the beam splitter and divides evenly into two beams. The sample beam, reflected by the moving mirror, travels through a glass plate four times, as does the reference beam, which is reflected by the fixed mirror. The setup ensures that the beams will travel through the glass an equal number of times before combining.

Key:
- Green = Initial Beam
- Purple = Sample Beam
- Yellow = Reference Beam
- Pink = Recombined Beam

Glass plate preceding beam splitter
Beam splitter
Compensating plate

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Thus, with the addition of the compensating plate, the sample beam and reference beam travel functionally identical paths, each passing through the equally-sized glass plates a total of four times. The reflected (sample) and transmitted (reference) beams recombine, and their interference pattern can be observed on the viewing screen. The viewing screen is a surface that produces a diffuse reflection so the interference pattern can be safely viewed.

It should be noted that while the fixed mirror is not adjusted during data collection, it can be tilted via a knob for alignment purposes. The moving mirror is adjusted by turning the knob of a micrometer. For our setup, a straw was taped to the micrometer knob in order to allow the knob to be turned more slowly and precisely. The micrometer was used to determine the displacement of the mirror as fringes were counted on the viewing screen. There is a five to one reduction from micrometer displacement to actual mirror displacement for the micrometer we used.\(^4\)

**Experimental Procedure:** The experimental procedure was performed according to the process outlined in the corresponding Pacific Lutheran University Physics 499A “Michelson Interferometer” lab handout.\(^4\) The first step in conducting the Michelson Interferometer experiment to determine the laser’s wavelength, once set up in the manner described in the previous section, is to align the optical system so that an interference pattern of circular fringes is observed on the viewing screen. The experimenter must be careful during alignment as well as during data collection to avoid looking directly into the laser beam or the reflective surfaces it hits – both cases have the potential to cause eye damage, and safety goggles may be worn for this reason.

There are several components of the system which one may need to adjust to achieve the desired interference pattern, including the orientation (height and angle) of the laser as well as the diverging lens through which it passes, the tilt of the fixed mirror, and the initial location of the moving mirror. If one observes two bright spots on the viewing screen – one from the fixed mirror’s reflection and one from the moving mirror’s reflection – the mirrors should be adjusted so that the two dots coincide and, thus, the two beams recombine into one.\(^5\)

After the aforementioned parameters were adjusted, a portion of the bulls-eye pattern of Figure 1 (best described as a quarter of a circle consisting of approximately five to ten rings) was observed on the viewing screen. It was concluded, and our results support, that while the ideal full bulls-eye pattern was not observed, a portion of this pattern was sufficient for counting fringes, as \(N\) will have the same value for a single changing interference pattern regardless of where on the pattern the observer is counting fringes.

Once such a pattern is observed, data collection may begin. To aid in counting, we placed pieces of black tape – spaced approximately one ring apart - onto the viewing screen, and counted the number of fringes that passed between the pieces of tape. The experimenter may consider incorporating this into the setup to improve the ease of the counting process.\(^6\) We assumed standard temperature and pressure. We then noted the initial position of the micrometer and slowly moved the micrometer in a counterclockwise direction while counting the fringes that passed through the tape on our viewing screen. (It is not necessary to turn the micrometer counterclockwise so long as the experimenter is consistent.) We chose to make \(N\) the independent variable and recorded the distance the micrometer moved after 100 fringes were counted for each trial. (The experimenter need not count 100 fringes, but should note that a \(\Delta d\) significantly larger than the uncertainty of the micrometer is desirable; hence, a large \(N\) is favorable.) In order to keep as accurate a count as possible, we both counted the fringes. We also alternated the task of adjusting the micrometer so that each experimenter could become familiar
with the apparatus. We conducted four trials, counting 100 fringes and recording the displacement of the micrometer for each trial.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Initial Position of Micrometer (mm)*</th>
<th>Final Position of Micrometer (mm)*</th>
<th>Displacement of Micrometer (mm)</th>
<th>Wavelength (nm)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.035</td>
<td>16.195</td>
<td>0.160</td>
<td>640</td>
</tr>
<tr>
<td>2</td>
<td>16.345</td>
<td>16.500</td>
<td>0.155</td>
<td>620</td>
</tr>
<tr>
<td>3</td>
<td>16.500</td>
<td>16.660</td>
<td>0.160</td>
<td>640</td>
</tr>
<tr>
<td>4</td>
<td>16.660</td>
<td>16.820</td>
<td>0.160</td>
<td>640</td>
</tr>
</tbody>
</table>

*The uncertainty of the micrometer is ± 0.005 mm, or ± 5 microns.
**The uncertainty of the wavelength was calculated to be ±28nm.

Table 1: The displacement of the micrometer and wavelength calculated for four trials. The displacement of the micrometer is the path-length difference of the sample beam and reference beam of the Michelson Interferometer after 100 fringes were counted. The wavelength was calculated using Equation 3. The uncertainty associated with the position of the micrometer is the smallest subdivision of the micrometer divided by two. The uncertainty of the wavelength was obtained via calculation. Trials for which the final position of one is the initial position of the other were performed consecutively.

Results: After calculations were performed using Equation 3 and the data recorded in Table 1, the corresponding wavelengths were obtained. Error analysis of our data yielded an uncertainty of 28 nm for the wavelength. In this analysis, N was treated as a constant. The average value for the wavelength over these four trials is 635 nm, and the standard deviation (σ) 10 nm. Thus, our final result for λ was 635 ± 28 nm, σ = 10 nm. This was compared to the value quoted in the lab handout of 633 nm, and to the standard value of a He-Ne laser used in interferometry of 632.8 nm at standard temperature and pressure. Our measured value differs from the literature value by approximately 0.35%.

Discussion: We used the Michelson Interferometer to obtain a value for the wavelength of the He-Ne laser that differs only slightly from the expected value. Our results are supportive of the assertion that the Michelson Interferometer is a valid means of determining the wavelength of a light source, once sources of error are taken into account.

There are components of this experiment through which error could be introduced. The most notable of these is the ambiguity of defining the appropriate point to count a fringe shift: the micrometer moves, albeit slightly, between fringes, allowing the scenario of a slight displacement of the micrometer without a change in the number of fringes counted. This could lead to an underestimate or an overestimate of the wavelength.
Conclusion: The wavelength of a laser is an identifying characteristic. For future experiments utilizing the Michelson Interferometer to determine a light’s wavelength, one may consider using a laser of unknown type. The measured wavelength could then be used to determine the laser’s identity. This could protect against the temptation to manipulate data in order achieve a result most near that which is expected and could also motivate careful measurement.

While it is not used for the purpose it was originally designed, the Michelson Interferometer is well-suited for a relatively quick measurement of the wavelength of a light source, and for a simple confirmation of the wavelike nature of light.

References:


4. “Michelson Interferometer” lab handout, Physics 499A – Capstone, Fall Semester, 2017, Pacific Lutheran University.

5. Amrita Vlab 2013, Michelson Interferometer – Amrita University, online video, viewed 20 September 2017, https://www.youtube.com/watch?v=lzBKlY4f1XA
