Application of a Michelson Interferometer for the Measurement of Laser Wavelength, the Refractive Index of Air, Sodium (Na) Spectrum Lines, and the Position of White Light Fringes

Department of Chemistry & Physics, Augusta University, Augusta, Georgia, USA
25 February 2019

In this laboratory experiment, we report the application of a Michelson Interferometer for the measurement of laser light wavelength, of the index of refraction of air, of the spacing between Sodium (Na) lines, and of the position of white light fringes for the Interferometer used in the experiment. We report a value of $\lambda = 631 \pm 8$ nm, which is within one standard deviation of the known quantity\(^1\) of 632.8 nm. For the determination of the index of refraction of air we report a value $n = 1.00026 \pm 0.00012$, which is within a standard deviation of the known magnitude\(^2\) of 1.00028. For the wavelength spacing between the Na lines we measured a quantity of $\Delta \lambda = 0.595 \pm 0.012$ nm, which is within one standard deviation of the tabulated value\(^3\) of 0.597 nm. Finally, we report white light fringes at a position of $d = 8.092 \pm 0.001$ mm for the mirror of the Michelson Interferometer.

I. INTRODUCTION

This laboratory experiment explores the applications and techniques of the Michelson Interferometer. The Michelson Interferometer, named after its inventor physicist Albert Michelson, is essentially an instrument used to produce interference between two beams of light\(^4\). Before discussing how this is done and how the Michelson Interferometer works, it is important to review the concept of wave interference in terms of electromagnetic radiation. According to the theories of electromagnetism and quantum physics, light behaves like both waves and particles. Like conventional waves, light waves have peaks and valleys as well as a phase. Interference occurs when two or more light waves interact with each other\(^5\). There are different types of interference, such as constructive interference when two waves in phase with each other add together, and destructive interference when two waves have equal amplitude in opposite directions and cancel each other out\(^5\). The physics of interference can be observed in any physical system where waves propagate. The Michelson Interferometer uses the properties of light interference for experimental measurements and observations. Like other interferometers, this optical device is used to measure the effects of interference by splitting beams of light and creating fringe patterns\(^6\).
The interferometer operates by first splitting a light source along two different paths of unequal distance\(^4\). After being separated by a beam-splitter the two light beams are reflected off of mirrors and brought back together in order to create an interference pattern on a screen or wall. One common feature of Michelson Interferometers is a compensation plate or lens that is used to establish equal optical path length for the two beams when the two mirrors are equidistant from the beam-splitter\(^4\). Three qualities which are commonly measured by using the Michelson Interferometer are geometrical path length, optical path length, and the index of refraction of various mediums\(^6\).

Measurements of optical path length, or the distance that one of the two mirrors is moved in order to change the fringe pattern, are the most common measurements made with the Michelson Interferometer. This measurement was made for every task, with the exception of the measurement of the refractive index of air, in this laboratory experiment. The first task where the distance of travel of the mirror was measured was in the determination of the wavelength of a red HeNe laser. There are numerous properties intrinsic of red HeNe lasers which make them useful for this experiment: the monochromatic nature of the wavelength, the propagation of the waveform as a sine-wave with singular amplitude and phase, and the spatial constancy of radiation along the width of the beam\(^7\). An additional benefit of using a HeNe laser is the enhancement of timing measurements and signal strengths due to the fast rise time of such lasers\(^7\). Measurements of the mirror distance and the number of fringes passing as the mirror moved were used to determine the wavelength of the red HeNe laser (refer to Equation 1)\(^6\).

\[
2\Delta d = \lambda\Delta m
\]  
(1)

In this equation, \(\Delta d\) represents the distance traveled by the mirror of the Interferometer, \(\Delta m\) represents the number of fringes propagated for the distance \(\Delta d\), and \(\lambda\) represents the wavelength of the laser light. Thus, the measurement of the red HeNe laser light wavelength is straightforward, with the procedure and results found below in the corresponding sections. For the second task, the only one in which the mirror distance was not measured, the red HeNe laser was again used to set up a fringe pattern. The only difference in the setup to find the index of refraction of air to that of the determination of laser light wavelength was the addition of a vacuum cell directly in front of the moving mirror. This vacuum cell was oriented so that the optical path of the separated laser beam passed through the cell. The pressure and length of the vacuum cell,
as well as the number of fringes counted, were used to calculate the index of refraction of air (refer to Equation 2)².

\[ n = 1 + \frac{\lambda m_{\text{room}}}{2Lp_{\text{vac}}} \]  

(2)

In the equation above, \( n \) represents the refractive index dependent on the laser light wavelength, the number of fringes, the room and cell pressures, and the length of the vacuum cell. New terms \( L, p_{\text{room}}, \) and \( p_{\text{vac}} \) represent the vacuum cell length, room pressure, and vacuum cell pressure, respectively. The index of refraction of air is a dimensionless quantity which describes how light will propagate in the medium of air. Refractive indices are important properties within the field of optical physics and in the study of optical instrumentation. The procedure and results of this task can be found below in the corresponding sections. The third task in this Michelson Interferometer laboratory experiment involved the measurement of the spacing between Sodium (Na) lines. The spectrum for Na is dominated by two lines within the range of visible light², having known values of 588.9950 nm and 589.5924 nm. The two interference patterns caused by these Na lines combine and, when maximized, have an optical path difference that is an integer multiplier of the two wavelengths⁸. Distance measurements must be made for the purpose of finding the wavelength spacing between the Na lines. However, the number of fringes is difficult to count for this task since the Na light source, which was a Na lamp, is not ideal for generating clearly visible fringe patterns. However, there are mirror distances that the Na lamp will not show a fringe pattern at all. These are known as washouts, and the number of washouts over a change in optical path length can be used to determine the wavelength spacing (refer to Equation 3). Therefore, we can rearrange the equation above in order to determine the wavelength spacing for the Na lines⁸.

\[ \Delta \lambda = \frac{\langle \lambda \rangle^2}{2\Delta d} \]  

(3)

In the equation above, the wavelength spacing is represented by \( \Delta \lambda \) and the average wavelength of the Na spectral lines has a known value⁸ of \( \langle \lambda \rangle = 589.1941 \) nm. The value \( \Delta d \) refers to the average spacing per unit washout, or break in the fringe pattern in the mirror from the Na lamp light. The procedure and results for this task of the experiment can be found in the corresponding sections below. The final task in this Michelson Interferometer experiment was the
measurement of the mirror distance at the condition of white light fringe propagation. For this task the first step was to use the experimental setup from the first task in order to find the equal difference condition, also known as the zero pathlength difference, between the interference patterns. When a white light source is incident on the Michelson Interferometer, white light fringes propagate at a mirror distance near the equal difference condition. The entire procedure for this task, as well as the corresponding results, can be found in the appropriate sections below.

II. PROCEDURE

As previously mentioned, there were four tasks completed for this Michelson Interferometer laboratory experiment: determination of laser light wavelength, calculation of the index of refraction of air, measurement of the wavelength spacing between Na lines, and the positional condition which white light fringes appear in the mirror of the device. The materials used for this laboratory experiment included: a Michelson Interferometer (refer to Figure 2), a red 632.8 nm HeNe laser tube, a phone camera for video recording purposes, a software plotting program, a vacuum cell and handheld pump, a Na lamp and power supply, a white light source, and a reflective surface for the Na lamp and the white light source. The first step of the first task was to setup the HeNe laser so that the laser beam was incident on the Michelson Interferometer (refer to Figure 1) and created a fringe pattern (refer to Figure 4) on the screen. The second step involved using the fine adjustment dial, which is one of two dials used to change the mirror distance, while recording video footage of fringes passing by. For each video of fringe pattern changes there was an initial and final distance measurement made for the mirror distance. The final step of the wavelength measurement task was to count the number of fringes in each video in order to determine the values of total fringes counts over the length of mirror distance change. These values (refer to Table 1) were used to calculate the red HeNe laser wavelength.
Michelson Interferometer

![Diagram of Michelson Interferometer]

**Figure 1.** Schematic of the basic Michelson Interferometer. The laser used in this experiment was a 1135/P JDSU 632.8 nm Helium-Neon Laser. Notice that the beam-splitter separates the laser beam into two different paths, and that the mirrors cause reflection of both beams. Not shown in the diagram are various lens for orientation purposes, as well as a compensation lens so that all beams travel through the exact same length of glass.

**Experimental Setup**

![Photo of 1135/P JDSU 632.8 nm Helium-Neon Laser]

**Figure 2a.** Photo of the 1135/P JDSU 632.8 nm Helium-Neon laser used for the experiment. The first task of the experiment was to use this laser to create a fringe pattern and verify the wavelength of the red laser light. **Figure 2b.** Photo of the Michelson Interferometer used for the experiment. Notices the two mirrors, the parallel beam-splitter and compensation lens, and both the gross and fine adjustment dials.
The second task employed the same experimental setup as the first task with the added addition of a vacuum cell placed directly in front of the moving mirror (refer to Figure 3). The red HeNe laser was again used to generate a fringe pattern on the screen, and video footage was recorded to analyze and count the number of fringes that passed by, just like in the first experimental task. The fringe pattern would move and propagate fringes as air was reintroduced to the evacuated vacuum cell. Measurements included the pressure of the vacuum cell before reintroducing air and the number of fringes counted. These were used to find the index of refraction of air. The third task involved mirror distance measurements at each Na lamp washout. The distance measurements were plotted and linearly fit in order to find the distance per unit washout and the wavelength spacing between Na lines. The fine adjustment was used to locate washouts. Similarly, the fine adjustment was used to find the white light fringes for the final task.

**Michelson Interferometer with Vacuum Cell**

*Figure 3.* Exact same schematic of the Michelson Interferometer as seen in Fig. 1 with the addition of a vacuum cell of length $L = 3.8$ cm between the beam-splitter and the moving mirror. This setup was used in order to measure the index of refraction of air by evacuating the vacuum cell of any air molecules and then reintroducing air to the cell in order to count the fringe pattern changes on the screen.
III. RESULTS & ANALYSIS

As previously stated, there were four tasks completed in this Michelson Interferometer laboratory experiment: determination of red HeNe laser light wavelength by counting fringes, measurement of the index of refraction of air using a vacuum cell and fringe counting, calculation of the spacing between Na lines by locating washouts of fringe patterns, and measurement of the mirror distance at the condition of white light fringe propagation. For all four tasks the Michelson Interferometer was employed as the central instrument. The first two tasks involved counting fringes in order to determine wavelength and the index of refraction of air, respectively. For the former, according to the physics behind the fringe pattern (refer to Equation 1) we needed to calculate the wavelength of the red HeNe laser based on measurements of the number of fringes that pass by for a change in distance. This task was carried out according to the procedure in the previous section. Nine data points for fringe counts and mirror distance were made via analysis of the nine videos recorded for the moving fringe pattern (refer to Table 1). It was made sure that a clear and visible fringe pattern (refer to Figure 4) was established while taking data for this experimental task.

<table>
<thead>
<tr>
<th>Trial</th>
<th>m</th>
<th>$d_i \ (mm) \pm 0.001 \ mm$</th>
<th>$d_f \ (mm) \pm 0.001 \ mm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>264</td>
<td>9.115</td>
<td>9.198</td>
</tr>
<tr>
<td>2</td>
<td>325</td>
<td>9.198</td>
<td>9.301</td>
</tr>
<tr>
<td>3</td>
<td>315</td>
<td>9.301</td>
<td>9.401</td>
</tr>
<tr>
<td>4</td>
<td>328</td>
<td>9.401</td>
<td>9.505</td>
</tr>
<tr>
<td>5</td>
<td>331</td>
<td>9.505</td>
<td>9.610</td>
</tr>
<tr>
<td>6</td>
<td>351</td>
<td>9.610</td>
<td>9.719</td>
</tr>
<tr>
<td>7</td>
<td>225</td>
<td>9.719</td>
<td>9.790</td>
</tr>
<tr>
<td>8</td>
<td>210</td>
<td>9.790</td>
<td>9.856</td>
</tr>
<tr>
<td>9</td>
<td>277</td>
<td>9.856</td>
<td>9.943</td>
</tr>
</tbody>
</table>

Table 1. Data points for the red HeNe laser light wavelength measurement task. For each trial there are three values which were measured: the number of fringes which propagated (m), the initial distance ($d_i$), and the final distance of the mirror ($d_f$). The final distance of one trial is equivalent to the initial distance of the succeeding trial since the fine adjustment dial was not changed between trials. Counts for each trial began with the propagation of a new fringe so that the last fringe on the previous trial was not counted twice. Error in the distance measurements comes from instrumental error of the Michelson Interferometer.
HeNe Fringe Pattern

Figure 4. Fringe pattern generated from the experimental setup of the red HeNe laser and the Michelson Interferometer for the purpose of counting fringes and measuring the red laser light wavelength. This fringe pattern was also used to find the equal distance condition for a rough approximation of the location of white fringes. The fine adjustment dial of the Michelson Interferometer was used for counting purposes, and the gross adjustment dial was used to find the equal distance condition.

From the data points (refer to Table 1), we calculated the total number of fringes over the data set to be $\Delta m = 2626$, and the total change in distance of the mirror via the fine adjustment dial was $\Delta d = 0.828 \pm 0.001 \text{ mm}$. Using these end points spanning the whole set of data the red HeNe laser light wavelength was found to be $\lambda = 631 \pm 8 \text{ nm}$. Uncertainty in the calculation comes from the instrumental error of the Michelson Interferometer mirror ruler and gross adjustment knob indicator, which was not turned during completion of the task but was useful since there is also a measurement reading on the dial. The uncertainty was turned into a percent uncertainty and multiplied with our result for wavelength in order to find the absolute wavelength uncertainty. Our measured value for the red HeNe laser wavelength falls well within one standard deviation of the known value\(^1\) of $\lambda = 632.8 \text{ nm}$.

The second task completed for this laboratory experiment was the measurement of the index of refraction of air by using the same setup as the first task with, as explained in the procedure, a vacuum cell magnetized onto the device directly in front of the moving mirror (refer to Figure 3). The cell was evacuated of air, with measurements of the initial counting pressure made by viewing the handheld vacuum pump dial. The cell was then slowly reintroduced to air,
causing the fringe pattern of the HeNe laser to move and propagate more fringes. In order to find the index of refraction of air (refer to Equation 2), the following measurements were made: length of the vacuum cell, number of fringes counted, and the vacuum cell pressure at the start of counting. The known value\(^1\) of \(\lambda = 632.8\) nm was taken as the wavelength of the red HeNe laser as and room pressure is known to have a value of \(p_{\text{room}} = 76.0\) cm Hg. Analysis of the video recorded for fringe counting purposes resulted in \(m = 25\) fringes propagating. This is a precise value with no error since we can analyze the video fringe-by-fringe. The vacuum cell was measured to have a length of \(L = 3.80 \pm 0.02\) cm. The pressure of this vacuum cell at the start of fringe counting, according to the reading of the handheld vacuum pump, was measured to be \(p_{\text{vac}} = 62.0 \pm 0.2\) cm Hg. Entering these values into the correct equation (refer to Equation 2), and making sure that proper unit conversion was used, we calculated a value of \(n = 1.00026 \pm 0.00012\) for the index of refraction of dry air. Note that the index of refraction is a unitless, or dimensionless, property since it a multiplier for refraction purposes. Our measured value falls within one standard deviation of the known quantity\(^2\) of \(n = 1.00028\). Uncertainty in the measured value resulted from instrumental error of the handheld vacuum pump and the measurement of the vacuum cell length. The percent error for each uncertainty was determined, added together, and multiplied by the final result for the index of refraction of air in order to find the total uncertainty of the measurement.

The third task in this Michelson Interferometer laboratory experiment was to find the spacing between the two Na lines by using the Interferometer, a Na lamp, and a reflective surface as specified by the procedure section. Data points (refer to Table 2) consisted of the washout number and the position of the mirror. Experimental setup was correctly carried out according to the procedure so that the Na lamp light reflected off a white paper surface so that a fringe pattern was clearly visible in the Michelson Interferometer mirror. The fine adjustment dial was turned until the fringe pattern was no longer visible, indicating a washout. As stated, the distance for each washout was recorded. Twenty-five data points were measured and tabulated below.
Table 2. Data points for the task of measuring the spacing between Na lamp light lines. For each washout (n) the distance (d) was recording. It was made sure that distance measurements were made only when the fringe pattern was no longer visible in the mirror of the Michelson Interferometer. Uncertainty in the distance measurements of the mirror arise from the instrumental error of the Interferometer device.
From the data points above a software program was used to construct a linear fit in order to find the value of $\Delta d$ (refer to Figure 5). Since the linear fit plotted the distance measurements against the corresponding washout numbers, the slope represents the spacing per unit washout. The value for the slope, or the distance per unit washout, is $\Delta d = 0.2919 \pm 0.0006$ mm/n. Using the relation between fringe patterns, Na lines, and the measured value for spacing per unit washout (refer to Equation 3) we calculated the value for the wavelength spacing between the Na lines. The known values\(^3\) for the two Na lines are 588.9950 nm and 589.5924 nm, with an average value of $\langle \lambda \rangle = 589.1941$ nm. Using this quantity and the value we found for the spacing per unit washout, we determined that the wavelength spacing between the two Na lines has a magnitude of $\Delta \lambda = 0.595 \pm 0.012$ nm. This is within one standard deviation of the known value\(^3\) for the Na spectrum line wavelength spacing, which is $\Delta \lambda = 0.597$ nm. The uncertainty in this measurement comes from the instrumental error of the Michelson Interferometer rulers. The uncertainty for our measured wavelength spacing was found from the percent error of the distance measurements.

![Distance (mm) vs. Washout Number (n)](image)

**Figure 5.** Plot and linear fit of the distance measurements and washout number for the Sodium (Na) lamp line spacing task of the experiment. The blue dots represent the distance measurement of the mirror on the Michelson Interferometer at each washout, or absence of fringe patterns, found for the Na lamp. The blue line represents the linear fit of all the data points. The slope represents the distance per unit washout, and this was used to find the wavelength spacing of the Na lines.
The final task of this laboratory experiment was to find the condition at which white light fringes propagate in the mirror of the Michelson Interferometer. This task was carried out according to the procedure, with a white light source shining on a white surface and reflecting onto the beam-splitter and mirrors of the Interferometer. The first step for this experiment was to find the equal distance condition of the fringe pattern by once again using the red HeNe laser. Once this was found, the white light source was established, and the fine adjustment dial was slowly turned until white light fringes were located. Other than the position where light white fringes propagated there was only the blank white image of the reflective surface, identical in appearance to the washouts of the Na line spacing task. The position of the mirror where white light fringes propagated (refer to Figure 6) was determined to be $d = 8.092 \pm 0.001$ mm. The uncertainty again arises due to the instrumental error of the Michelson Interferometer ruler.

**White Light Fringes**

![Figure 6. Photo of the white light fringes found for the final task of the experiment. The first step in this process was using the red HeNe laser to find the equal distance condition of the fringe pattern. The second step involved the positioning of a white light lamp and white paper reflective surface, and then using the fine adjustment dial of the Michelson Interferometer to find the white light fringes. Notice the colors between the fringes.](image)

**IV. CONCLUSION**

In summary, there are numerous physical quantities which can be measured by direct use of a Michelson Interferometer. As mentioned in both the abstract and the results section, the
following values were found by using this interferometry device: the wavelength of red HeNe laser light, the index of refraction of $n$, the spacing between Na lines, and the position of the device mirror at the condition of white light fringe propagation. For the red HeNe laser light wavelength, a value of $\lambda = 631 \pm 8$ nm, which is within one standard deviation of the known value\(^1\) of 632.8 nm, was found. The index of refraction of dry air has a known value\(^2\) of 1.00028, and our measured quantity of $n = 1.00026 \pm 0.00012$ is also within one standard deviation of the known. For the wavelength spacing of the Na lines we measured a value of $\Delta \lambda = 0.595 \pm 0.012$ nm. This is one standard deviation of the known value\(^3\) of 0.597 nm. For the white light fringe experimental task, we found that at a mirror position of $d = 8.092 \pm 0.001$ mm the white light fringes (refer to Figure 5) would propagate. In general, operating the Michelson Interferometer and understanding the physics behind interference is straightforward and not too complex. However, there was uncertainty present in all final results, which indicates that improvements are possible for each task conducted. For example, there are perhaps more precise and accurate ways to count fringes or find the equal distance condition. More fringes could be counted for the purpose of finding the red HeNe laser wavelength, which would result in a more precise measurement. The same is true if more data was taken for the Na lamp task. As far as the white light fringes go the method and experiment is straightforward and does not need much in the way of improvement. In conclusion, there are many optical experiments which can be conducted with a Michelson Interferometer in order to measure a number of physical values and constants.

V. REFERENCES