Michelson Interferometer

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(Dater: December 1, 2022)

This calibration and use of a Michelson Interferometer was investigated. A Michelson interferometer. The interferometer was calibrated, used to measure wavelengths of unknown frequencies of light, separate spectral lines, find the index of refraction of a thin sheet, and find the bandwidth of an optical filter.

I. INTRODUCTION

The Michelson Interferometer was developed in the late 1800s by Albert Michelson, its most famous use was in the Michelson-Morley experiment performed in 1887 which ruled out the luminiferous aether as a light bearing fluid and set the stage for the development of special relativity by Einstein in 1905. The interferometer design is currently used to detect gravitational waves in observatories such as LIGO, VIRGIO, and KAGRA which detected the first gravitation waves.

This interferometer also has some uses interferometry for astronomy but many of those have been supplanted by the Fabry-Perot interferometer. These interferometers have uses in measuring unknown wavelengths of light, index of refraction, and thickness of thin transparent sheets, and determining distance between closely spaced spectral lines.

II. Theory

The Michelson interferometer operates on the principle of division of amplitude of the incoming light; incoming light is split by a beam splitter, and it passes through one of two arms at 90 degrees to each other. From these arms the light is recombined and observed by the operator who looks at the interference fringes through a lens.

The interferometer is constructed of two opposing arms with mirrors at their ends. Incoming light travels through a ground glass diffraction grating, it is then split by a beam splitter such that half travels down each arm, it reflects off mirrors M_1 and M_2 and is brought back together with the opposite side of the beam splitter. On the path to mirror M_2 there is a compensator so that both beams pass through the same amount of glass whichever side of the beam splitter they are on. Light is focussed by a lens and then viewed by the user who can see the interference patten caused by the different travel distances for the light paths. Alternating bands constructive and destructive interference creates a distinctive pattern of light and dark fringes when monochromatic light is observed.

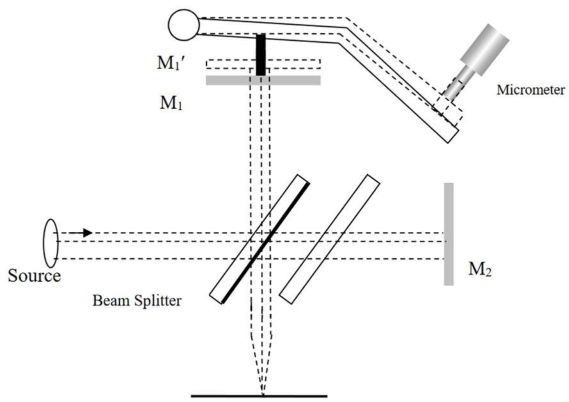

FIG. 1. The interferometer, the beam from the source is split by the beam splitter travelling the same distance between mirrors M_1 and M_2 and being recombined and into the viewer where fringes can be observed. From PHYS 3080 lab manual.

M_1 can be moved back and forth by the micrometer changing the distance travelled and shifting the fringes, this causes them to move past the viewer. M_2 can be rotated in 2 directions allowing the location on the fringe pattern to be changed. The interference pattern is circular where the mirrors are aligned. Circular fringes are near the centre of the overall pattern; vertical and horizontal fringes are observed when the mirrors are not aligned, as the angle of the mirror is increased the fringes become smaller and straighter.

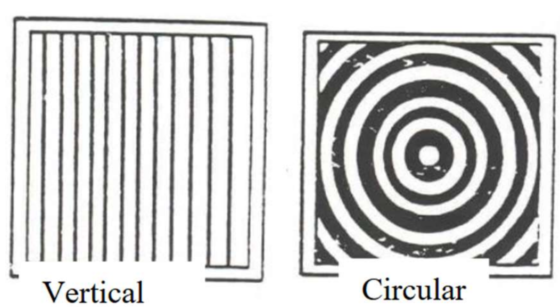

FIG. 2. Vertical and circular fringes as seen through the viewer; the vertical fringes are smaller and less defined than the circular.

A. Calibration

To use the interferometer to take precise measurements as in sections B-E, the calibration constant K is necessary, this constant is a measure of how much mirror M_1 moves for some distance of micrometer movement. For a change in micrometer reading ΔD and N fringes of wavelength λ passing the viewer K can be found as:

$$K = \frac{N\lambda}{2\Delta D}. \quad (1)$$

The position of zero path difference is another important parameter for calibration; it is the location of movable mirror M_2 where the light travels the same distance in each arm. Many of other measurements rely on knowing this location, and this is the location where the fringes are largest and easiest to observe. It is found with a white light source. When white light passes through the interferometer component wavelengths of white light will cause noise and produce a visible pattern near zero path difference.

B. Measuring wavelengths

With a known K unknown wavelengths of light can be measured; recoding the reading for a N fringes to pass the viewer. The unknown wavelength can be calculated with a slight change to (1),

$$\frac{2K\Delta D}{N} = \lambda. \quad (2)$$

This will work much better near the location of zero path difference.

C. Wavelength differences

The fringes from two of lines with slightly different wavelengths λ_1 and λ_2, where $\lambda_1 < \lambda_2$. These will overlap near 0 path difference but as M_1 moves further away this overlap will lessen. Eventually the one with the smaller wavelength will have travelled half a wavelength more than the other causing them to interfere destructively with each other, this will repeat on each side of the position of zero path difference causing alternating region of high and low visibility of the fringes. When moving from one position of low visibility to another exactly one more wavelength of the shorter one will pass the viewer than the longer,

$$2d = (N+1)\lambda_1 = N\lambda_2, \qquad (3)$$

where d is the distance between a position of high and low visibility. The total wavelength difference can then be determined:

$$\Delta\lambda = \frac{<\lambda>^2}{2d} = \frac{<\lambda>^2}{2K\Delta D}, \qquad (4)$$

with $<\lambda>^2$ as the apparent wavelength of the lines when combined.

D. Index of refraction

The optical path length Δ_p depends on the index of refraction n of the medium the interferometer is in, and the distance travelled d;

$$\Delta_p = 2dn. \qquad (5)$$

When a material of thickness t is placed in one arm of the interferometer the index of refraction of that material n is can be determined with:

$$\frac{K\Delta D}{2t} + 1 = n. \qquad (6)$$

E. Bandwidth

The bandwidth of a light filter can be found with the interferometer. Such filters are classified using their full width at half max, and their mean transmission wavelength. When white light is passed through one of these filters the visibility of the fringes will decrease away from the position of zero path difference until the fringes disappear and then reappear like the pattern formed by wavelength differences.

$$\Delta\lambda = 0.44\frac{<\lambda>^2}{K\Delta D}, \qquad (7)$$

where $K\Delta D$ is the distance between the half visibility sections, and $<\lambda>$ is the mean transmission wavelength of the filter which cannot be measured with the interferometer.

III. Method

A Beck-Ealing Michelson interferometer was used for this experiment. For uncertainty of all values was reported with the SEM2 for a 95% confidence interval.

To set up the interferometer for a measurement first the device was focused by aligning the two images of a piece of tape placed on the diffraction grating. The angle of M_2 was then slightly varied to be slightly off of circular fringes and the image of the piece of tape was pointed to a fringe. To measure the distance of some number of fringes the micrometer reading was recorded for the start, it was turned until N fringes passed the tape, and the micrometer reading was again recorded; the difference between these values was the micrometer distance for N fringes. Using K as calculated in section A this could be converted to the actual distance. For all measurements multiple trials were taken and the mean value was used with the SEM2 as the error which was propagated through calculations.

A. Calibration

The position of zero path difference was first determined using a while LED flashlight. The flashlight was placed in the source and the micrometer reading of the central dark fringe was noted.

K, the calibration constant was found using data near this value. A mercury lamp was placed at the entrance to the interferometer with a green filter to isolate the 546 nm line (λ). The micrometer distance (ΔD), for 25 fringes (N) was recorded. These values were used in (1) to calculate the calibration constant K. The average of K over 10 trials was taken with the SEM2 as its uncertainty and was propagated for the rest of the calculations in this lab.

B. Measuring wavelengths

The wavelength of the sodium D line was measured in this section. A sodium lamp without a filter was used as the light source; using the same method for data recording as in A 10 trials were taken and (2) was used to calculate wavelength of the Na-D line.

C. Wavelength differences

Again, using the sodium lamp the differences between the 2 lines that make up the Na-D line were measured. Measuring the difference between positions of minimum fringe visibility on either side of the zero-path difference. Measurements were alternated between the side below the zero-path difference and that above it for 5 trials, the difference between each of these sets of values was used as ΔD in equation (2) with the average wavelength $< \lambda >$ of $589.3\ nm$ for find the wavelength difference $\Delta\lambda$.

D. Index of refraction

A thin piece of plastic with a thickness t of 0.094 mm was used. For the plastic the difference in positions of zero path difference with and without it was measured. Using these as ΔD the index of refraction was calculated with (6).

E. Bandwidth

The full width at half max can be found with an interferometer. A white led was again used as the light source, the position of zero path difference was found. Then the carriage was moved until the fringes were about half as visible as they were at 0 path difference. Measurements were alternated between either side of the 0 path difference moving the carriage back and forth. These were used as the ΔD in equation (7) to find the bandwidth of the filter. We used red mean transmission wavelength 650 nm, and green mean transmission wavelength 525 nm filters. The mean transmission wavelength was measured with a spectrometer.

IV. Results

A. Calibration

The position of zero path difference was located at a micrometer reading of 5.396 ± 0.002 mm. K was found using (1) as 0.2015 ± 0.0037.

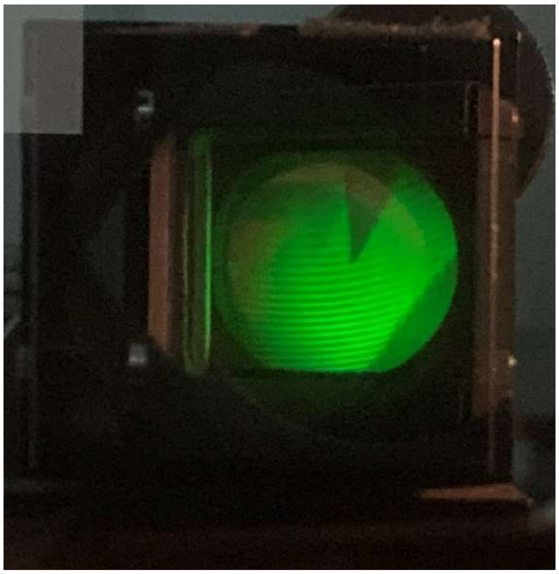

FIG. 2. Slightly curved horizontal fringes with the green mercury line.

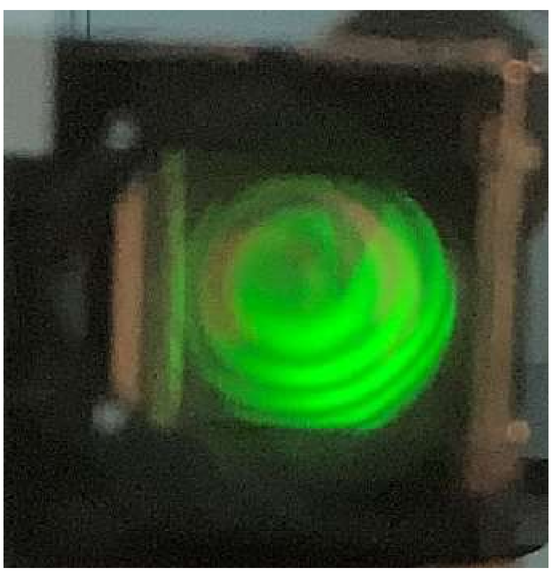

FIG. 3. Circular fringes with the green mercury line.

FIG. 4. The coloured fringes and the black lines of the position of zero path difference obtained with white light.

B. Measuring wavelengths

The wavelength of the sodium D line was found as $589 \pm 23\ nm$. This aligns with the literature value of 589.3 nm.

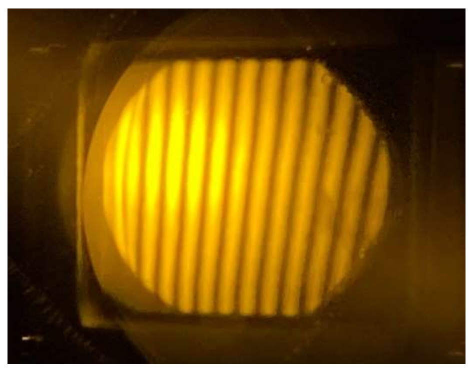

FIG. 5. Vertical sodium D-line fringes.

C. Wavelength differences

The distance between the two components of the Na-D line was measured 0.603 ± 0.029. In literature the two wavelengths are 589.5924 nm, and 588.9950 nm with a difference of 0.5974 nm matching our measured value.

D. Index of refraction

The index of refraction of the material was found as 1.405 ± 0.029. Using Wikipedia's List of refractive indices, this is probably Ethylene tetrafluoroethylene or a similar plastic ($n = 1.403$) and has the index of refraction as the human cornea.

E. Bandwidth

The bandwidth of the red filter was $94.3 \pm 4.3\ nm$, and the green one was $110 \pm 14\ nm$. We had no manufacturers values to compare these measurements against.

V. Discussion and Further Study

Operating the interferometer precisely was difficult. It was very difficult to move M_1 the small amounts necessary to take measurements. Even once I became used to the operation this still proved difficult. I began placing the elbow of the arm that was operating the micrometer on a lab jack to hold it more steady and allow for more precise measurements. Using an interferometer with finer control of the location of M_2 would have been controlled more finely eliminating errors in moving the mirror.

Even then it took many trials to get enough useful data to measure K to the level needed to do subsequent measurements. For all measurements more trials would have reduced the error and given better values.

The bandpass filter section of this lab was completed with filters that were in the lab. They had had no measurements of the bandwidth or mean transmission on them so the comparison could not be made.

VI. Conclusion

The tests performed in this lab demonstrate the uses of a Michelson interferometer and of interferometry more generally. We calibrated the interferometer to measure very small distances in wavelength and found the position of zero path difference. With this we were then able to measure the wavelength of an unknown light source, measure the difference in wavelength of a doublet spectral line, determine the index of refraction and identify a potential material for a thin sheet of plastic, and we measured the bandwidth of filters. Interferometry is a very useful technique from the gravitational wave detectors that utilize this to the several astronomy applications discussed in lecture.