Wavemeter

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ABSTRACT: By utilizing the sensitivity of a Michelson interferometer, the wavelength of an unknown laser is determined. A reference laser beam with wavelength 633 nm is collimated with the unknown laser beam and passed though the interferometer. By varying the length of one arm of the interferometer, an analysis of the fringe spacing caused by interference of the two lasers wavelike nature allows an estimation of the unknown lasers wavelength. Two different methods are used to gather data from this setup. Data capture from an oscilloscope connected to detection equipment at the end point of the interferometer found a wavelength of ~547.9 nm while usage of a high precision frequency counter in a similar fashion gave a wavelength of 543.55±1.8 nm.

INTRODUCTION: This experiment uses a double Michelson interferometer setup as shown in Figure 1. This setup is referred to as a wavemeter. [1]

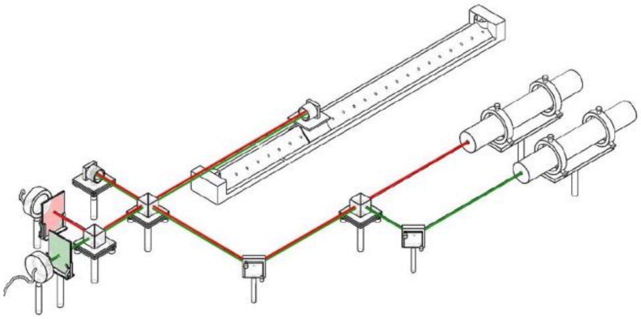


Figure 1: Diagram of wavemeter apparatus (Credit: UNM Senior Lab Manual)

The red laser shown above acts as our reference laser and the green laser is the "unknown" laser which we are determining the wavelength of. The air rail in the top center of the figure has a corner cube mirror on a glider that moves with very little friction. We found that a ~0.3 m portion of the air track provided the most uniform motion and all data was collected by constraining the glider to move only in that section. Figure 2 below provides a top down view of the wavemeter and a clearer view of the equipment involved.

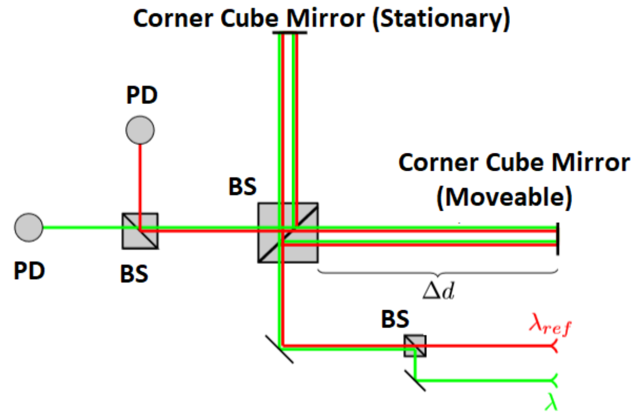


Figure 2: Top down view of wavemeter optics

Three beam splitters (BS) are used: one to combine the beams emanating from each laser (bottom right), one to split the combined beam along the two arms of the interferometer (center) and one to separate the beams before detection by a pair of photodiodes (PD). The air rail allows the moveable corner cube mirror to change position by an amount Δd.

Theory: It can be shown for a Michelson interferometer, and thus a wavemeter using such a device, the path length difference Δd between the two arms is given as

$$\Delta d = \frac{N\lambda}{2} \quad (1)$$

where N is the number of observed interference fringes and λ is the wavelength of the electromagnetic wave. By ensuring the two laser beams in this setup are along parallel paths, Δd will be identical for both laser beams. This gives the relation

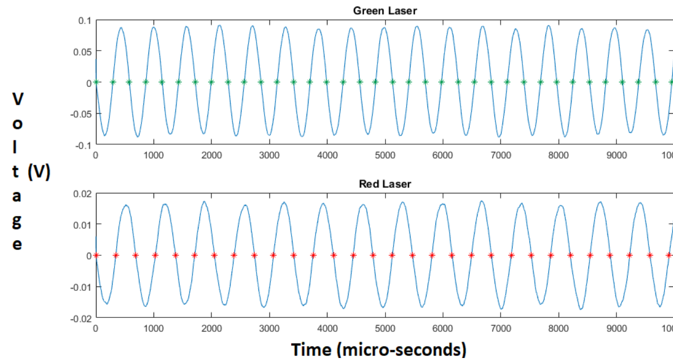
$$\frac{N_g \lambda_g}{2} = \Delta d = \frac{N_r \lambda_r}{2} \tag{2}$$

where the subscript 'g' and 'r' refer to the green and red laser respectively. Equation 2 allows us to solve for the wavelength of the unknown laser, λ_g, once the fringe counts detected at that lasers respective photodiode are counted per unit time.

Setup: Alignment of the optics is of the upmost importance. Our method was to use a flat mirror placed to interrupt the path of the combined beam just before it entered the second beam splitter pictured in the center of Figure 2. We then placed another flat mirror to reflect that beam onto the back wall of the lab ~10 m away. By adjusting the stage the combining optic was placed on, we worked to have the two colored beams focused at the same point on the wall. Next, we placed a small white card on the movable corner cube mirror and removed the mirror placed for the first adjustment. Our goal was to ensure that during movement of the air glider mounted corner cube mirror, the red and green dots produced by the two laser beams remained in the same position relative to the linear axis of the air rail.

Once our alignment procedures had brought the two laser beams into as parallel of path as possible, we worked to reduce noise. The beam splitter on the final leg of each beams journey is not perfect and will allow some transmission of red to the photodiode meant to capture photons from the green laser and vice versa. To minimize this noise, we placed filters that allow transmission of certain wavelength through and block unwanted wavelengths in front of their respective photodiodes. A corner cube mirror is used for both arms to ensure polarization of the laser light remains orthogonal with regards to each beam during their journey through the wavemeter.

Data analysis: Our first task after alignment was to see if our setup was providing data near to our expectations. A green He-Ne laser will have a wavelength of ~543 nm. [3] A plot of the intensity of each laser beam incident on the photodiodes is shown in Figure 3. This data was captured using an oscilloscope with a maximum resolution of 10^6 data points per second. A peak in the intensity of the waveform indicates constructive interference which is caused by the photons traversing both arms of the interferometer being exactly in phase with each other when striking the detector. Counting the number of zero crossings (indicated by the star), allows a determination of the number of fringes per a measured time period.



In order to reduced error caused by integer rounding of the fringe counts for each of the waveforms in Figure 3 only the zero crossings for a complete wave are counted. Solving for the unknown in Equation 2 we arrive at

$$\lambda_g = \frac{N_r \lambda_r}{N_g} \tag{3}$$

which allows us to estimate the wavelength of the unknown laser after counting the zero crossings for each laser in Figure 3 and inputting the λ_r value of 633 nm. 20 sets of data were taken, and an averaging of the fringe ratio and standard deviation gives a ratio of 0.8655 ± 0.0125. Using Equation 3 we arrive at an estimated wavelength for the unknown green laser of 547.9 nm. This value is several deviations away from the literature value of 543 nm, but it does give us confidence our alignment and experimental premise is sound.

A Phillips PM 6654 high resolution programmable timer/counter was used to obtain a more accurate measurement. This device takes the signals from the two photodiodes and calculates the ratio of peaks between each channel. This will provide a much higher resolution because the single shot sample rate is of order nanosecond vs the oscilloscopes microsecond sampling. This helps to ensure the number of fringes 'missed' due to sampling resolution is minimized. Table 1 shows some of the data captured for different gate widths.

10 ms	.1 s	1 s	10 s
0.98912	0.858664	0.858649	0.859033
0.862069	0.858664	0.858885	0.890853
0.877193	0.858738	0.858885	0.914562
0.934579	0.858664	0.858657	0.858649
0.862069	0.858664	0.858885	0.858649
0.877193	0.858664	0.858657	0.951267
0.900901	0.858738	0.858664	0.858649
0.833333	0.858664	0.858664	0.858959
0.892857	0.858738	0.858664	0.858649
0.892857	0.607903	0.858649	0.958892
0.900901	0.858664	0.858657	0.858804
0.884956	0.858664	0.858664	0.858649
0.877193	0.858738	0.858664	0.858649
0.859107	0.858738	0.858664	0.858649
0.859107	0.858664	0.858657	0.907342
0.858369	0.858811	0.858634	0.858959
0.859107	0.858664	0.85859	0.858649
0.606061	0.858738	0.859107	0.858657
0.859845	0.858664	0.858664	0.858664
0.858074	0.858738	0.858664	0.858649
0.859107	0.858664	0.858738	0.872448
0.857633	0.858664	0.858664	0.927584
0.859107	0.858738	0.858738	0.858649
0.859107	0.858811	0.858664	0.858657
0.859107	0.862069	0.858664	0.920641
0.858369	0.858738	0.858664	0.858716
0.880282	0.858664	0.858664	0.868885
0.87184	0.859107	0.858664	0.865067
0.862069	0.859107	0.858657	0.861946

Table 1: Data collected by the high precision counter. Top row is gate time and ratios are N_g / N_r for all other rows.

By computing the variance of each data column, we can choose a gate time that provides the most consistent results. For our data sets a gate time of 1 second had the lowest variance by two orders of magnitude compared to the next closest gate time variance. An average of the collected ratios for the 1 second gate time provides a ratio of 0.8587 ± 0.0001. Again, using equation 3 a wavelength for the unknown green laser is 543.55 nm.

Error is present in the stated wavelength of the known red laser as well as in the measurement and averaging of the frequency counter data. Since these errors are uncorrelated they must be added in quadrature to provide an accurate error estimation for the resultant green laser wavelength. Equation 4 gives the formula used to calculate that error.

$$\sigma = \lambda_g \sqrt{\left(\frac{\sigma_r}{\lambda_r}\right)^2 + \left(\frac{\sigma_N}{N}\right)^2} \qquad (4)$$

Where λ_r and λ_g are the red and green laser wavelengths respectively, σ_N and σ_r are the standard deviation of the fringe counter ratio data and the red laser wavelength, and N is the number of fringes counted. The standard deviation of the red laser is given as 0.5 nm according to the laser label. The number of fringes counted, N, is estimated in the lab manual to be ~10^6 per unit time for Δd of 30 cm. Combining these values with the standard deviations of the red laser and calculated value of the green laser wavelength we use the above equation to arrive at a value of ±1.8 nm for our error in the green lasers wavelength.

Conclusion: The double Michelson interferometer setup in this fashion provides an excellent way to measure the wavelength of an unknown laser provided the reference laser has an accurately known wavelength. The data provided by the oscilloscope allowed us to refine our setup and the programmable counter provided a very precise measurement of the ratio of interference fringes. Our calculated value of 543.55±1.8 nm for the wavelength of the green laser is within 0.1% of the provided value of 543 nm.

REFERENCES:

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[2] Wikipedia contributors. "Michelson interferometer." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 18 Feb. 2018. Web. 10 Apr. 2018.

[3] https://www.rp-photonics.com/helium_neon_lasers.html