# Inferring the Index of Refraction of Indium Tin Oxide Conducting Glass Using Interferometry

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## Abstract

Optical coherence tomography (OCT) is a non-invasive imaging technique, which offers faster and higher resolution imaging than conventional methods, and does not make contact with the sample. An OCT scanner uses a Michelson interferometer, which splits a light source into two beams, then recombines the light. In order to gain a better understanding of the theory guiding OCT, as well as the implementation of it in a lab setting, we built a Michelson interferometer. We verified the functionality of our Michelson interferometer by comparing interference patterns and comparing beam intensities with the interference equation. We then used our Michelson interferometer to measure the index of refraction of materials; in particular, the primary sample material is indium tin oxide (ITO) conducting glass, a well characterized optoelectronic material. With our Michelson interferometer, we were able to measure an average index of refraction of 1.42, which is close to the reported value of 1.53.

## Introduction / Background

Non-invasive imaging techniques and non-destructive testing methods are crucial in the biomedical field and for industrial metrology [1]. For example, they are used to image internal structures in biological tissues [6] and diagnose various retinal diseases [1][11]. In addition, they are used in industrial quality control, investigation of production processes, and materials characterization in research and development [11]. These non-destructive testing methods are needed in situations when conventional excisional biopsy is hazardous, impossible, or has a high false negative rate because of sampling errors [5]. Also, they are useful in circumstances where preserving the original status of a sample is important or when investigating precious objects [11].

Conventional non-destructive testing methods, such as ultrasound imaging, exhibit low imaging resolutions of hundreds of microns, and typically require direct contact between the probe and the sample. It is also fairly restricted in terms of speed [2]. These drawbacks led to the development of a non-invasive imaging technique known as optical coherence tomography (OCT). OCT offers faster and higher resolution imaging, with a high resolution of 1–15 μm and penetration of 2–3 mm in human tissue [9], without contacting the sample. However, there are still several challenges that must be overcome for the widespread application of OCT [2]: the need for better lateral resolution, the need for increased axial imaging range, miniaturization of OCT imaging instruments, and production of real-time images.

The main component of the OCT is a Michelson interferometer (Figure 1) [10]. The monochromatic light source is then passed through a half-silvered mirror, or a beam splitter, which splits the light into two beams. These beams are sent to two reflectors: one is at a fixed distance, and the other is sent to a sample or different reflector at an unknown distance. The two beams are then recombined, and the resulting phase difference can be measured with a photodetector, which can then be used to the distance of the sample from the Michelson interferometer.

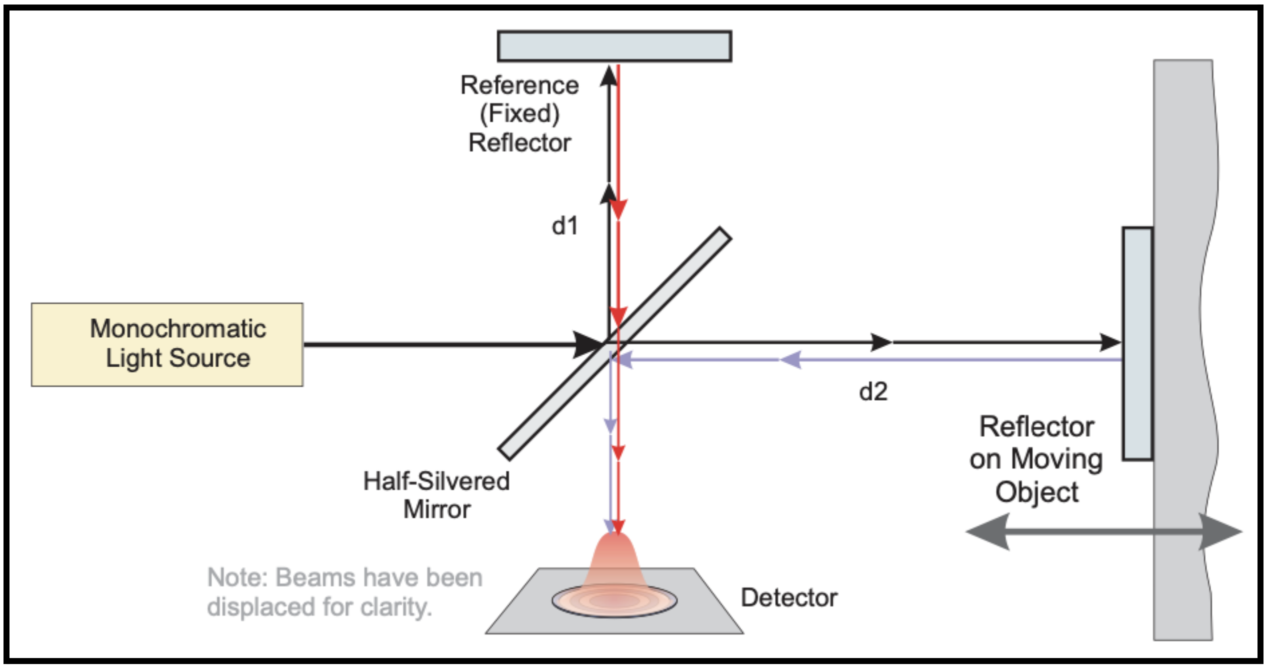


**Figure 1**: Schematic of a basic Michelson interferometer.

In order to gain a better understanding of the theory guiding OCT, as well as the implementation of it in a lab setting, we will build a Michelson interferometer using a red laser. After verifying the functionality of the Michelson interferometer, we will use it to measure the index of refraction of materials.

There have been OCT studies carried out for a variety of materials, including polymers, semiconductors, metal oxides, glasses, and ceramics [11]. We will use indium tin oxide (ITO) conducting glass [7] — widely used as transparent semiconductor oxide electrode materials in organic/inorganic heterojunction, Schottky, CdTe, and other thin film solar cells — as the primary sample material. Because there has been previous research done on measuring properties of indium tin oxide conducting glass using OCT [12], the results of this work can be assessed. Overall, these results can then be used to prototype a Michelson interferometer similar to the one we build in an OCT scanner.

## Methods

*Control Setup - Verifying the Functionality of the Michelson Interferometer*

We first constructed a Michelson interferometer, similar to Figure 1, on an optical bench (Figure 2). We used an aluminum mirror and a silver mirror, and attached them to a Thorlabs Single-Axis Translation Stage with Differential Adjuster, in order to move them by small distances (25 μm of translation per revolution). We did not attach anything onto the mirrors, so that we could have a control setup. The photodetector was connected to a Newport Optical Power Meter Model 1916-C, which gave us intensity measurements of the laser beam.

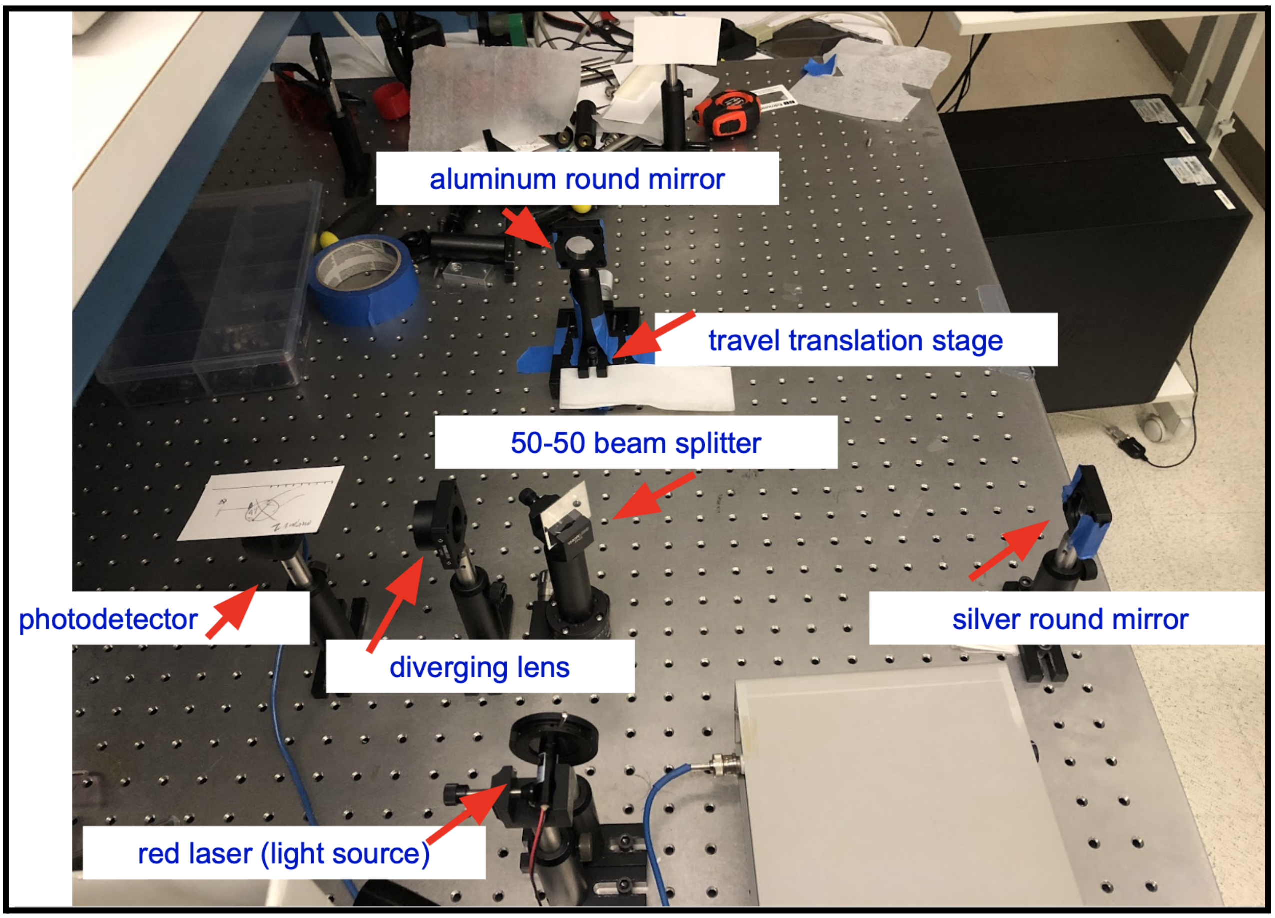


**Figure 2**: Our setup of the Michelson interferometer.

We used our control setup in order to verify the functionality of the Michelson interferometer. We performed two different analyses with this control setup. For our first analysis, we compared the interference pattern produced with the control setup with an interference pattern that was reported by previous work (Figure 3) [3].

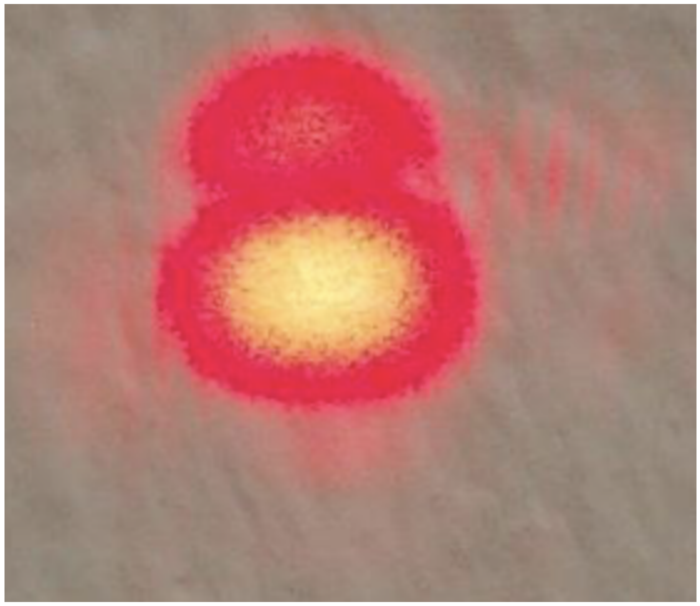

**Figure 3**: Interference pattern reported in the literature.

From wave optics, the interference of two beams can be described by Equation 1. Here, $I_{Total}$ is the intensity of the combination of the two beams, $I_S$ is the beam to and from the sample mirror, and $I_R$ is the beam to and from the reference mirror, and ΔΦ is the phase difference between these two beams. Equation 2 describes the relationship between the phase difference (ΔΦ) and the difference in distance that the beams are delayed by (Δd). In this equation, k is the wavenumber, which is given by 2π / λ, where λ is the wavelength of the light source. Since we used a red laser as the light source, λ ≈ 630 nm - 670 nm [4].

**Equation 1**: $I_{Total} = I_S + I_R + 2\sqrt{I_S I_R} cos\Delta\phi$

**Equation 2**: $\Delta\phi = k\Delta d = \frac{2\pi}{\lambda}\Delta d$

Rearranging Equation 1, we have:

**Equation 3**: $cos\Delta\phi = \frac{I_{Total} - I_S - I_R}{2\sqrt{I_S I_R}}$

For our second analysis, we measured $I_{Total}$, $I_S$ (by blocking the beam to and from the reference mirror), and $I_R$ (by blocking the beam to and from the sample mirror). We plotted this as a function of tick rotation on the travel translation stage, which is Δd. Since Δd and ΔΦ are linearly related, the plot should resemble a cosine curve, as shown in Equation 3.

*ITO Setup - Measuring the Index of Refraction of Indium Tin Oxide (ITO) Glass*

After verifying the functionality of the Michelson interferometer, we measured the index of refraction of the ITO glass. To do so, we attached the ITO glass sample onto the silver round mirror (Figure 4). This was the only change made to our Michelson interferometer (Figure 5).

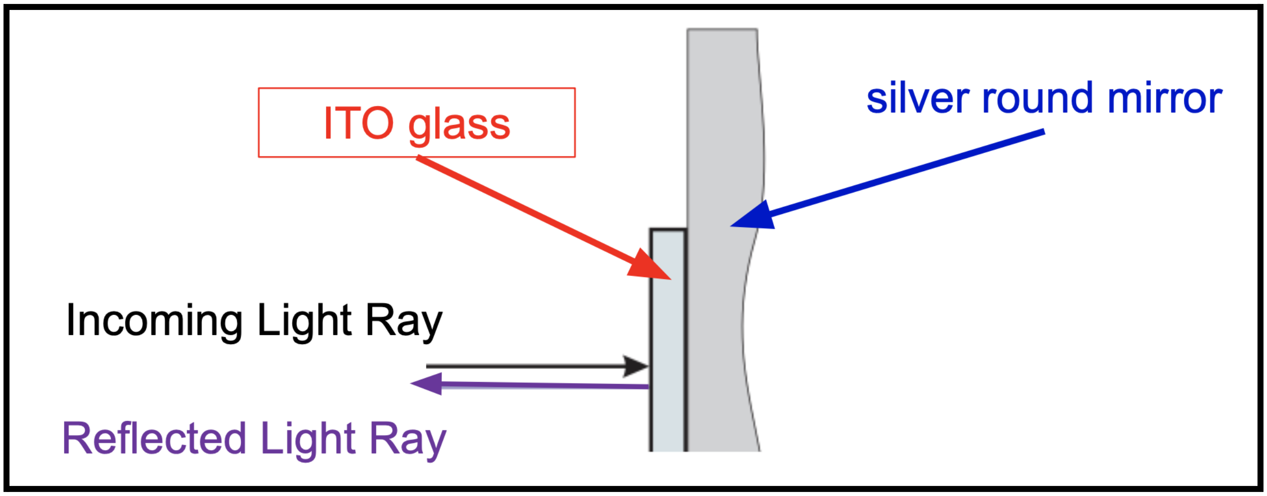


**Figure 4**: The modified sample mirror that now includes the ITO glass.

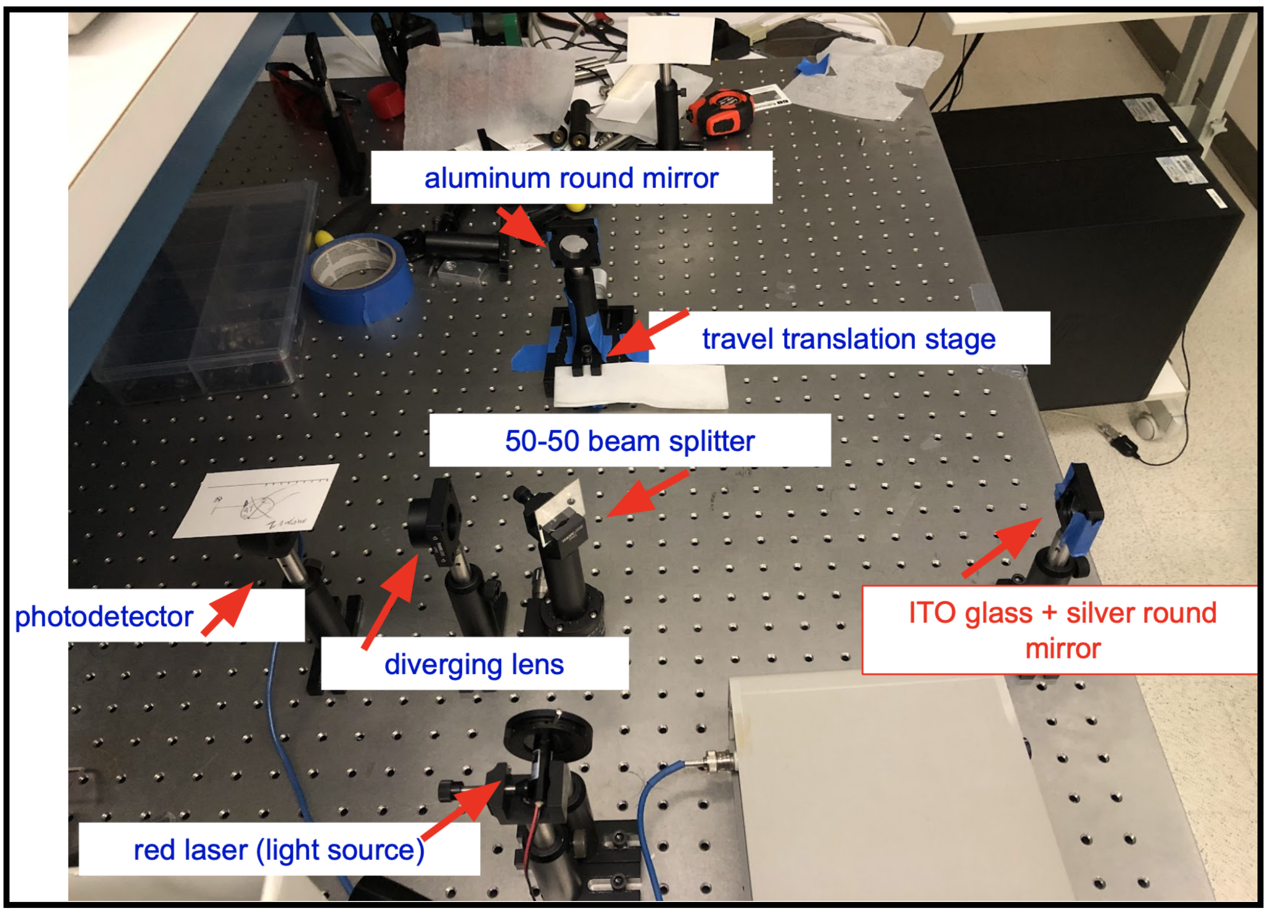


**Figure 5**: Inclusion of the ITO glass in the Michelson interferometer.

In order to measure the index of refraction of the ITO glass, we modified the setup that was used in previous research, which also used Michelson interferometer to determine the index of refraction of various liquids (Figure 6) [8].

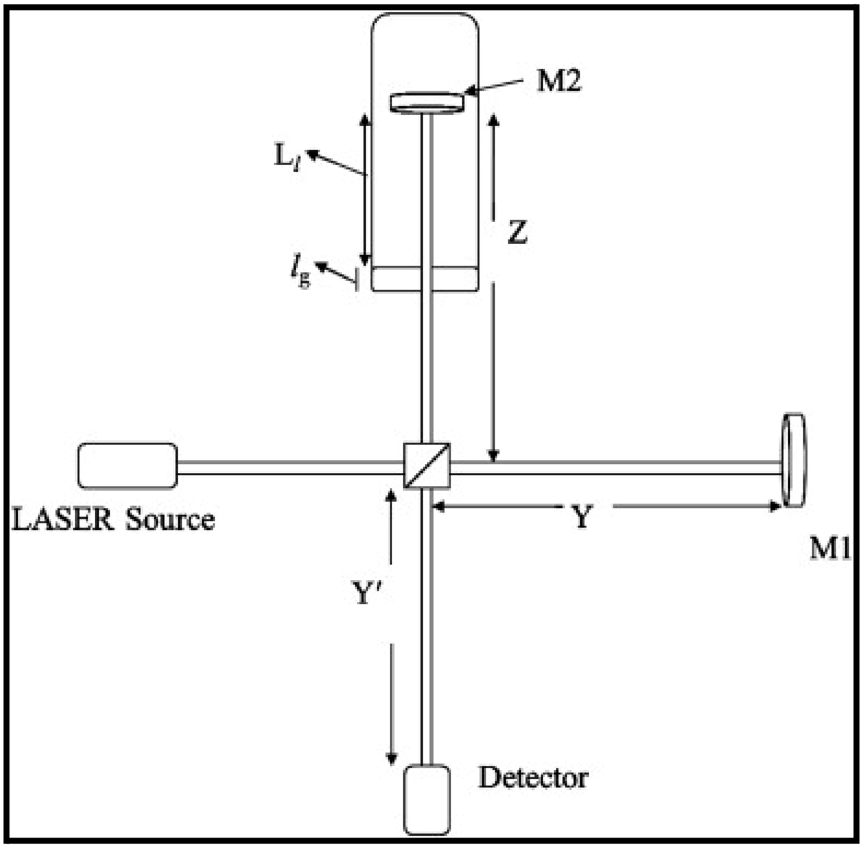


**Figure 6**: Michelson interferometer setup used to determine the index of refraction of various liquids.

In this setup, M1 is the reference mirror and M2 is the sample mirror. Y is the distance from the beam splitter to the reference mirror, Y' is the distance between the beam splitter and the photodetector, and Z is the distance between the beam splitter and the sample mirror. This setup used a sample chamber, which had a glass quartz window, with thickness $l_g$ and index of refraction $n_g$, and the liquid, with thickness $L_l$ and index of refraction $n_l$.

The path length in this setup used the definition of optical path length, as described in Equation 4 with medium 1 being air ($n_1 \approx 1$), with Equation 2. Note that the beam travels to and from each of the mirrors, which is why there is a coefficient of 2 before all the terms (except for Y', since the beam does not reflect from the photodetector). The final result is shown in Equation 5.

**Equation 4**: $Optical\ Path\ Difference = n_1 l_1 - n_2 l_2 = l_1 - n_2 l_2$

**Equation 5**: $\Delta\phi = k\Delta d = k[(2Z - 2l_g - 2L_l + 2n_g l_g + 2n_l L_l + Y') - (2Y + Y')]$

Our procedure does not involve a chamber with a liquid inside of it; we only use the ITO glass as the sample. Therefore, the terms with $n_g$ or $l_g$ will be 0, so the Equation 4 simplifies to the following:

**Equation 6**: $\Delta\phi = k\Delta d = k[(2Z - 2L + 2nL + Y') - (2Y + Y')] = k(2Z - 2Y - 2L + 2nL)$

Rearranging and solving for n:

**Equation 7**: $n = \frac{\Delta\phi - 2k(Z-Y)}{2kL} + 1$

Equation 7 can be used to calculate the index of refraction of the ITO glass by calculating $\Delta\Phi$ through $I_{Total}$, $I_S$, and $I_R$ in Equation 3, and measuring Z, Y, and L.

## Results and Discussion

*Control Setup - Verifying the Functionality of the Michelson Interferometer*

We were able to observe the interference pattern from our control setup (Figure 7). These images were taken using a phone camera; the image on the left shows the fringe pattern from our control setup with the room lights on, and the image on the right shows the fringe pattern from our control setup with the room lights off. Comparing this with the interference pattern shown in Figure 3, they are similar in terms of the locations of the bright and dark spots. They also have a similar spread of fringes.

(a) | (b)

**Figure 7**: Fringe pattern from our control setup (a) with room lights on (b) with room lights off.

We also measured the intensity of the combined laser beams ($I_{Total}$), and the constituent beams ($I_S$ and $I_R$), and plotted the expression in Equation 3 (Figure 8).

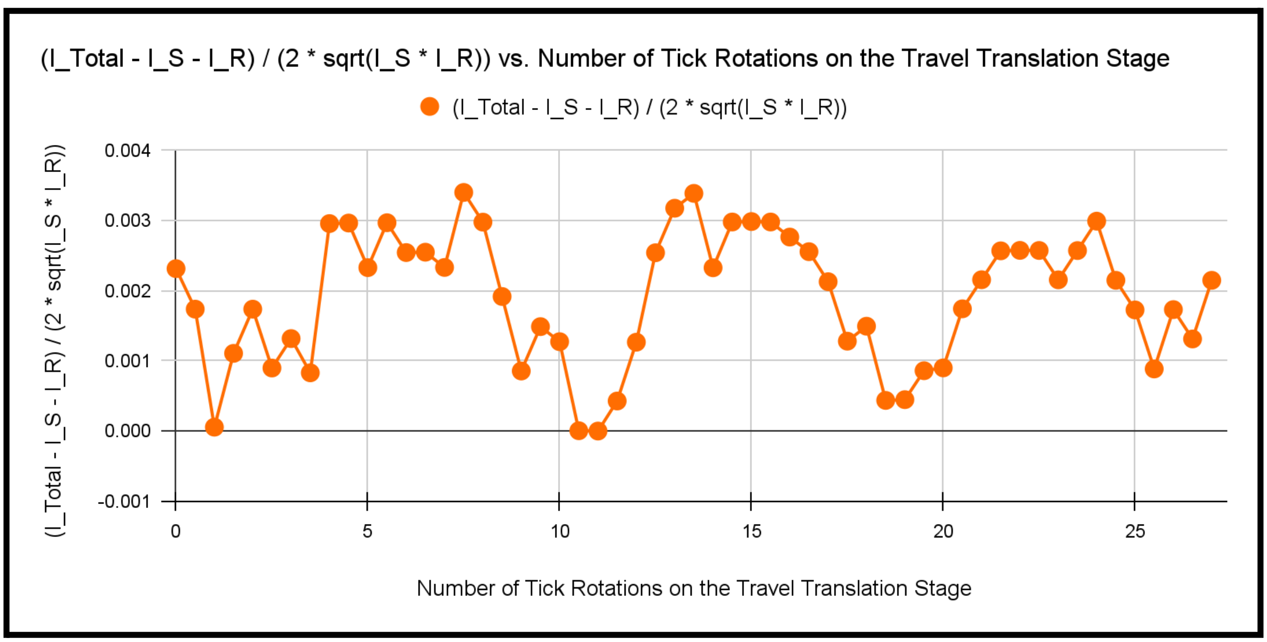


**Figure 8**: Plot of the interference equation, as measured by our control setup.

As shown in the plot, we observe a graph that resembles a cosine function. The plot does not resemble a perfect cosine function, as there was some noise in our measurements. We tried to reduce the noise by turning off the lights, but there were variations in the intensity measurements.

*ITO Setup - Measuring the Index of Refraction of Indium Tin Oxide (ITO) Glass*

Next, using Equation 7, we measured the index of refraction of the ITO glass, and repeated the procedure for various positions on the sample (Figure 9 and 10).

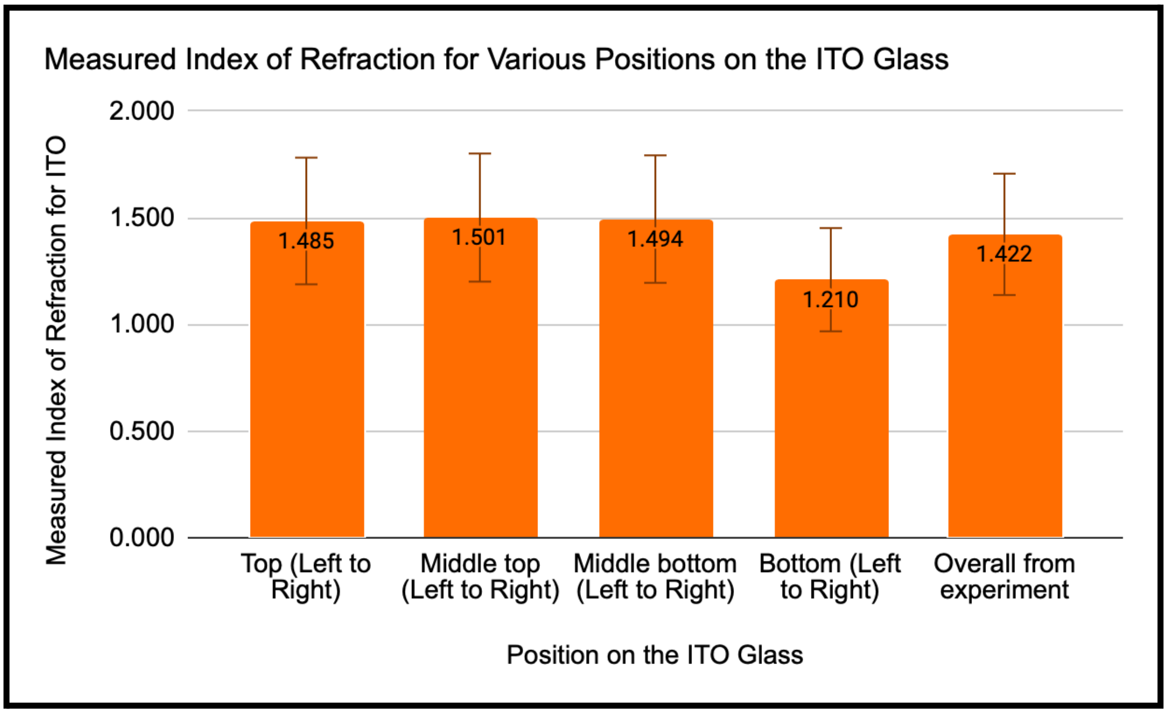


**Figure 9**: Measured index of refraction for various positions on the ITO glass sample.

| Position on the ITO glass | Averaged Refractive Index | Standard Deviation |
|---|---|---|
| Top Region (Left To Right) | 1.485 | 0.2999 |
| Middle Top Regions (Left To Right) | 1.501 | 0.2999 |
| Middle-Lower Regions (Left To Right) | 1.494 | 0.2866 |
| Lower Regions (Left To Right) | 1.210 | 0.1398 |
| Average of All Positions | 1.422 | 0.2917 |
| Published Index of Refraction: 1.53 ± 0.0559 [12] | | |

**Figure 10**: Averages and standard deviations of the measured index of refraction various positions on the ITO glass sample.

Our results show that the average measured index of refraction of the ITO glass was very close to the reported index of refraction. The published index of refraction always fell within one standard deviation of our average measured index of refraction. However, we had much higher standard deviations than the reported value. This was likely due to measuring errors and noise from the environment, or from the misalignment of the components of the Michelson interferometer.

## Conclusion

In this work, we were able to successfully set up a Michelson interferometer on an optical bench in the lab setting. We were also able to measure an average index of refraction of 1.42 for the ITO glass, which is very close to the published value of 1.53. There are still some improvements that can be made to further improve its accuracy, including but not limited to aligning the components of the Michelson interferometer better, reducing noise, etc.

Now that we have a working Michelson interferometer, this can be used as the foundation for an OCT scanner. One could use infrared radiation to perform OCT, and develop an algorithm to reconstruct an image of the defects in ITO, which has also been done in previous research.

## References


1. Adolf Friedrich Fercher "Optical coherence tomography," Journal of Biomedical Optics 1(2), (1 April 1996). https://doi.org/10.1117/12.231361
2. Bradu, A., Marques, M., Rivet, S., & Podoleanu, A. (2018, August). Current capabilities and challenges for optical coherence tomography as a high impact non-destructive imaging modality. In Seventh International Conference on Lasers in Medicine (Vol. 10831, p. 108310E). International Society for Optics and Photonics.
3. Build and use a Michelson interferometer. Apache2 Ubuntu Default Page: It works. (n.d.). Retrieved December 11, 2021, from http://spiff.rit.edu/classes/phys216/workshops/w14x/michelson/michelson.html.
4. Echnical information P - usaphc.amedd.army.mil. (n.d.). Retrieved December 11, 2021, from https://usaphc.amedd.army.mil/PHC%20Resource%20Library/cv19-cleaning_and_disinfection_guidelines.pdf.
5. Fujimoto, J. G., Pitris, C., Boppart, S. A., & Brezinski, M. E. (2000). Optical coherence tomography: an emerging technology for biomedical imaging and optical biopsy. Neoplasia, 2(1-2), 9-25.
6. Huang, D., Swanson, E. A., Lin, C. P., Schuman, J. S., Stinson, W. G., Chang, W., ... & Fujimoto, J. G. (1991). Optical coherence tomography. science, 254(5035), 1178-1181.
7. Ito Coated Glass. TECHINSTRO. (2021, November 8). Retrieved December 11, 2021, from https://www.techinstro.com/ito-coated-glass/.
8. Kachiraju, S. R., & Gregory, D. A. (2012). Determining the refractive index of liquids using a modified Michelson interferometer. Optics & Laser Technology, 44(8), 2361-2365.
9. Lamirel, C., Newman, N. J., & Biousse, V. (2010). Optical coherence tomography (OCT) in optic neuritis and multiple sclerosis. Revue neurologique, 166(12), 978-986.
10. Loughridge, R., & Abramovitch, D. Y. (2013, June). A tutorial on laser interferometry for precision measurements. In 2013 American control conference (pp. 3686-3703). IEEE.
11. Stifter D. (2015) Nondestructive Material Testing Using OCT. In: Drexler W., Fujimoto J. (eds) Optical Coherence Tomography. Springer, Cham. https://doi.org/10.1007/978-3-319-06419-2_85
12. Tsai, M. T., Chang, F. Y., Lee, Y. J., Lee, J. D., Wang, H. C., & Lee, C. K. (2011). Defect detection and property evaluation of indium tin oxide conducting glass using optical coherence tomography. Optics express, 19(8), 7559-7566.