An investigation of the effect of optical density on the intensity of different wavelengths of visible light

Gourav Pullela

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ABSTRACT

This paper explores a topic, under Wave Phenomenon, called polarization to answer the following research question: ***"What is the relationship between optical density of a polarizer and the intensity of different wavelengths of light?"***

A wave of light is said to be polarized when if the electric field off the wave oscillates on the same field. The purpose of this research paper is to investigate the effect of partial polarization on different wavelengths of light, and if possible, determine a general relationship between the intensity of light and its wavelength at a given angle of polarization. To determine this relationship, an experiment was designed, to test for a general trend in the visible light spectra, using red, green, and violet light. Using the raw data from the experiment, a relationship will be derived, and a general trend will be integrated.

The effect of polarization on real world applications is also studied, including the effect of polarization due to water, which affects the growth of aquatic plants, which are a crucial part of the aquatic ecosystem. There are many practical application that concern this topic, which is why it is the topic in study.

The effect of polarization of light can be applied to the concept of UV polarization. This can be use to prevent UV from harming our bodies.

The topics of polarization and light intensity are explored, and the applications of the experiment are discussed.

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INTRODUCTION

Polarization has many applications, whether it may be in photography or LCD screens. The reason I chose to work on polarization is due to my interests in photography and biology. The topic in focus is the effect of different levels and types of polarization on different wavelengths of light.

This topic has a fairly wide scope, and allows me to study the effects of polarization non aquatic plants, as well as the effect of the Doppler effect on the wavelength of light that is polarized. It is important to study the effect of polarization on the intensity of different wavelengths of light, because it can allow us to further understand the effect of different light sources on the growth of underwater plants, which are a crucial part of the aquatic ecosystem. The study of polarization can also us understand the effect of polarizing technology, such as that used in sunglasses, on our eyes.

Polarization and light phenomenon are still several concepts that are not entirely understood by the general population, even though these concepts affect our daily lives, through agriculture, our lifestyle and so on. My goal is to understand how polarization as a phenomena, behaves, when studying the concept with monochromatic light instead of polychromatic or white light. This could further help the general population in terms of agricultural efficiency, work efficiency, and so on.

BACKGROUND INFORMATION

Polarization is a phenomenon that takes place only in the case of electromagnetic waves, due to their transverse nature. Unlike sound waves which are mechanical or longitudinal, the direction of energy transfer in transverse waves is perpendicular to the direction of displacement.

The most common type of polarizer, found in sunglasses, liquid crystal displays, and optical microscopes, is called a Polaroid. Polaroid polarizers are thin film sheets with crystalline minerals known as dichroic materials, that absorb different amounts of light, from different wavelengths. These dichroic materials are arranged on the plane of polarization, and when electromagnetic waves are incident on the polarizer, the field oscillating on the plane of polarization is absorbed by the materials, polarizing the light. This the case for wire grid polarizers as well, where the only difference is that in place of dichroic materials, microscopic wire are used to absorb and polarize light. Light consisting of two plane waves, of equal amplitude, where the phase difference between both the waves is 90º, is said to be circularly polarized. This type of polarization can occur when linearly polarized light is passed through a quarter wave plate, which then slows down the light, producing an oscillating phase difference of 90º on both axes. Circular polarization helps when taking pictures and even in astronomy, to study the properties of cosmic dust.

Polarization can also occur naturally, in liquids such as water. As light passes through water, two phenomena take place - reflection and refraction. This plane polarization takes place due to the oscillation of water molecules on the surface of the water body, which absorb and reflect a portion of the photons incident on the surface of the water. Depending on the angle of incidence, the intensity of the light that is reflected and refracted changes. Due to this, depending on the time of day, aquatic plants receive different amount of sunlight. The name of the angle of incidence, when the angle between the reflected and refracted rays is 90º, is known as Brewster's Angle, named after Sir David Brewster, who contributed tremendously to the study of light phenomena. Outside of nature, polarization is also extensively used in lots of technology, including LCD screens and polarized sunglasses. In the case of sunglasses, the lenses used are polarized in on one plane, reducing the intensity of light on the eyes. However, in the case of liquid crystal displays, the reason polarizers are used, is to allow us to see the screen at a lower intensity which allows us to differentiate the colors. If there were no polarizers in LCD screens, the entire screen would appear white, which is why, linear polarizers are used to prevent that. Polarization is also used in film and photography. Circular polarizers reduce the amount of light that enters the aperture of cameras, and also help in reducing glare and reflections. There are two types of polarizing filters used in photography - Circular Polarizing Filters and Neutral Density Filters. Circular polarizing filters are used to reduce glare, get rid of reflections, and slightly reduce the intensity of light incident on the lens of the camera, whereas, Neutral Density

(ND) filters are used to produce optical density, solely to reduce the intensity of light going into the aperture, which allows for long-exposure photographs, and in film making, to reduce the light entering the camera's lens, without modifying camera settings. Malus' Law, named after Étienne-Louis Malus, a French physicist, is a relation used to explain the intensity of light when passing through one or more linear polarizers. This law was further adapted and used to form another mathematical relation that governs the relationship between the initial and final intensity of light after passing through a Neutral Density (ND) filter, where in Malus' law, the relationship was based on a trigonometry, but in this case is an exponential relationship, depending on the optical density of the filter.

Neutral Density filters are polarizers, made up of a combination of a linear and circular polarizers, that allows light to be polarized, but unlike a pair of linear polarizers, light is not entirely (100%) polarized. It is fractionally polarized. Anything that polarizes light produces optical density, that reduces the intensity of light reflected from an object, as perceived. ND filters produce optical density. Neutral Density values are standard values that ND filters are designed in, and each ND value corresponds to a certain optical density. For example, ***ND2*** corresponds to an optical density of ***0.3***. ND values are also directly related to fractional transmittance values.

MATHEMATICAL FORMULAS AND LAWS

- Malus' Law

  $I = I_0 \cdot \cos^2(\theta)$
  I = Intensity after polarization
  I_0 *= Intensity before polarization*

- Transmittance through Neutral Density Filters

  $$\frac{I}{I_0} = 10^{-d}$$

  D = Optical Density

- Brewster's Angle

  $$\theta_b = arctan\left(\frac{n_2}{n_1}\right)$$
  n_1 = refractive index of first medium
  n_2 = refractive index of second medium

- Doppler effect

  $$f' = f\left(\frac{v}{v-u_s}\right)$$
  f' = Apparent Frequency
  f = Actual Frequency
  u_s = velocity of source
  v = velocity of sound

DESIGN

The experimental setup involves the use of three different wavelengths of visible light, on either sides of the spectrum, and in the middle.

Materials

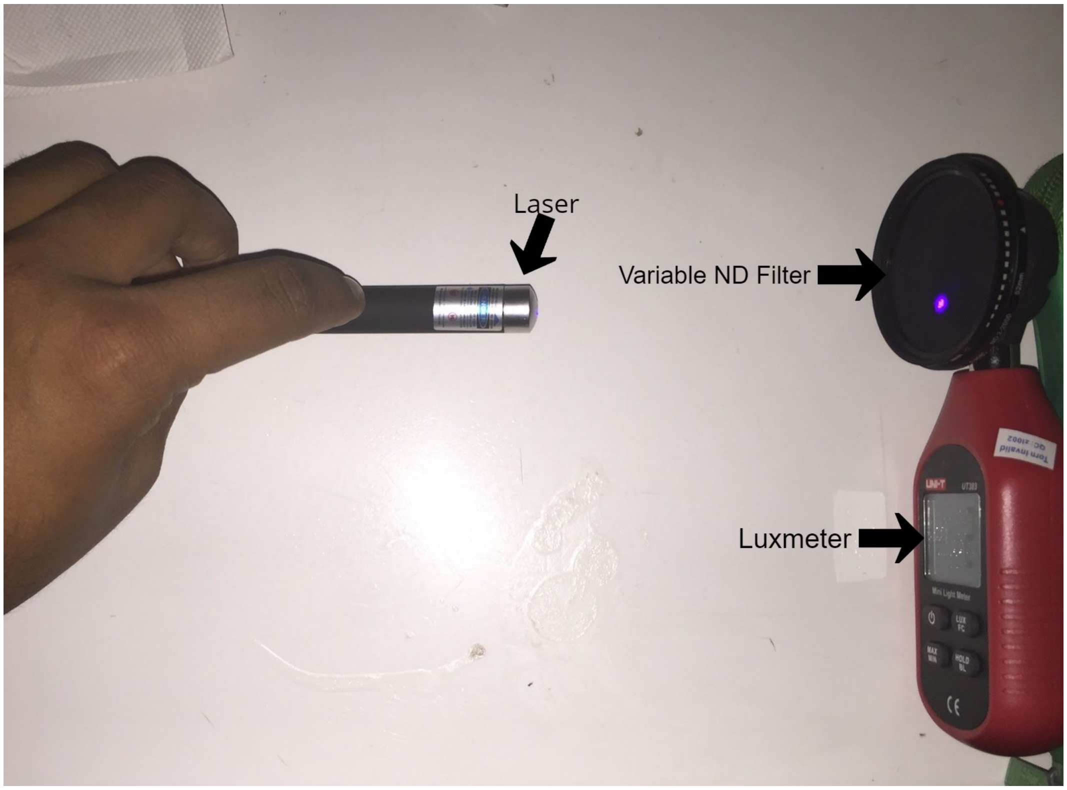
- ❏ 400-500 nm Laser - Violet
- ❏ 500-600 nm Laser - Green
- ❏ 600-700 nm Laser - Red
- ❏ Luxmeter
- ❏ Variable Neutral Density (ND) Filter
- ❏ Optical Bench (*Optional*)

The laser is placed at one end of the optical bench. The photometer being used is placed at the other end of the optical bench. A photometer is a device used to measure the intensity of light incident on it, without any major loss of power. The polarizer(s) being used is placed in between the laser and the photometer.

In the case of the variable ND filter, after every third reading, the ND value is increased, increasing the optical density of the polarizer, decreasing the intensity of light transmitted.

When conducting the experiment, using the variable neutral density filter, I chose to take two optical density values, from both the maximum and minimum sides. The ND values I chose were ND2, ND4, ND1000, and ND2000. For each laser, conduct three trials each, at each respective ND value, while also taking down the reading for the intensity of the light coming from the laser, without polarization.

A picture of the design of the experimental setup is given below.



The variable neutral density filter is place on the lux meter, for the readings after polarization. For readings before polarizing the laser light, the laser was directly pointed into the lux meter.

Precautions

Do not point the laser at the eyes, as they can damage the retina. Wear eye protection, such as polarized goggles.

Independent Variables

- Intensity of Light before polarization ($\boldsymbol{I_0}$)- The intensity of each laser may vary and the fractional transmittance of a color of light being emitted from a certain laser is the value of the intensity of light after polarization ($\boldsymbol{I_f}$) relative to the intensity of light before polarization ($\boldsymbol{I_0}$)
- Optical Density of Neutral Density Filters (n) - The ND value that the neutral density filter is set at determines the optical density of the filter, which in turn determines $\boldsymbol{I_f}$ and $\boldsymbol{T}$.

Dependent Variables

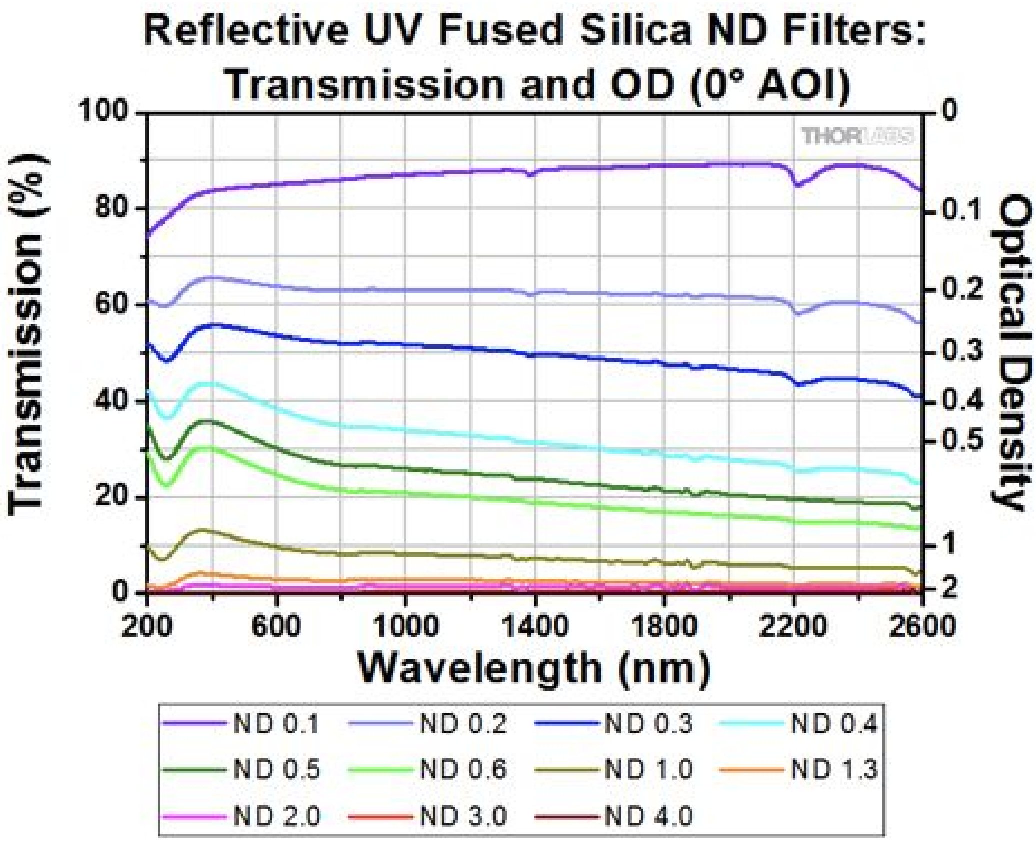
- Intensity of Light after polarization (***I_f***)- The polarization, due to the ND filter, affects the intensity of the light coming from the laser
- Fractional Transmittance of Light (***T***)- The relative amount of light transmitted by a light source after passing the light through an optically dense medium. This is calculated using the formula - $T = I_f / I_0$ - which gives a value which has no unit since it is a relative quantity.

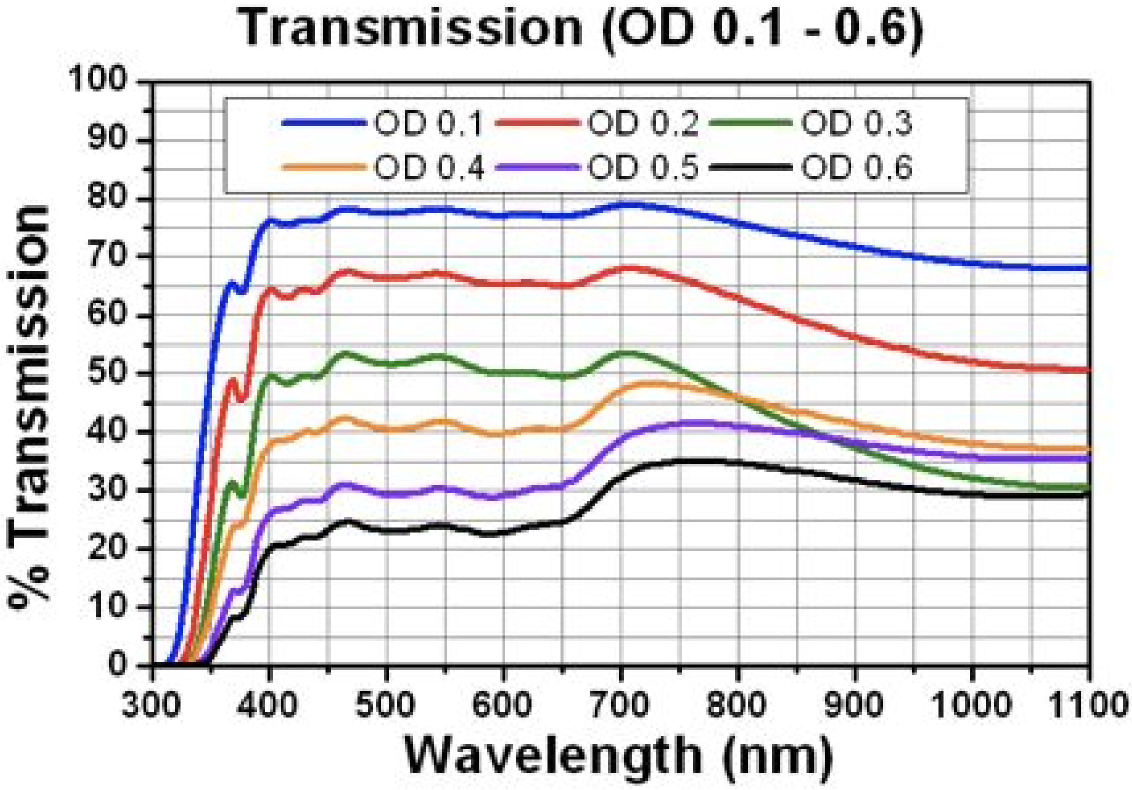
Controlled Variables

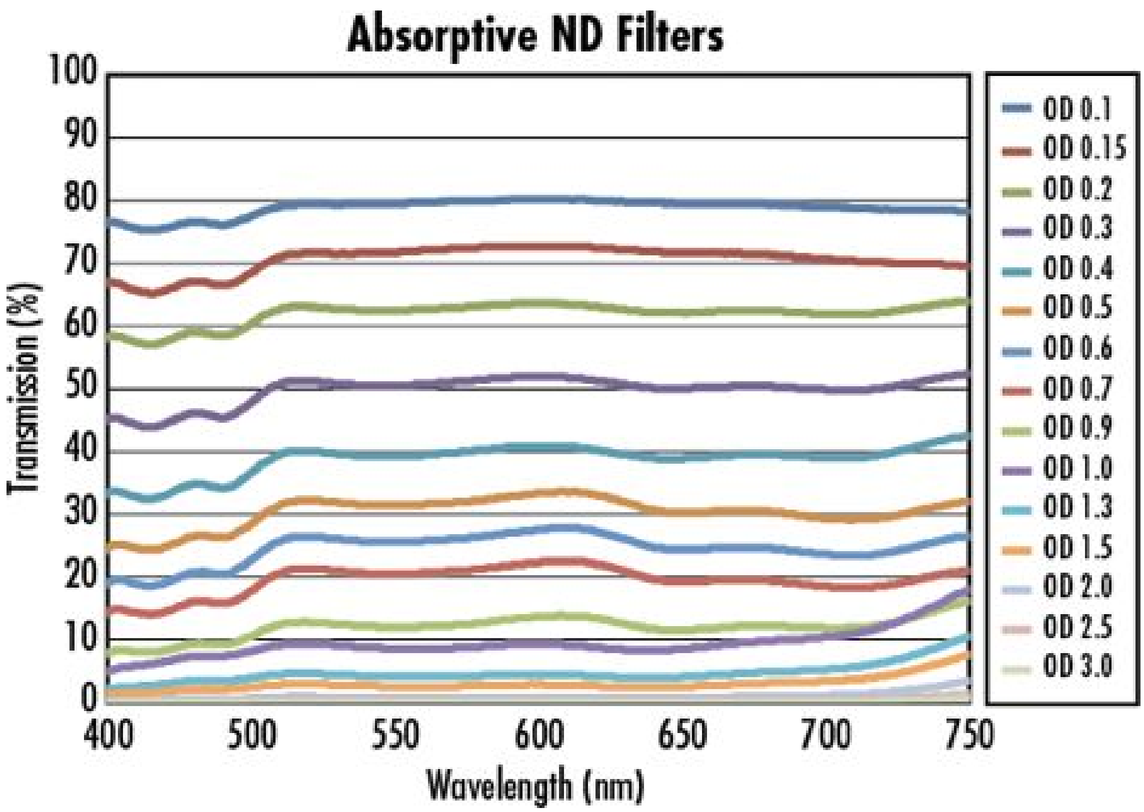
- Frequency of Light emitted from laser (***f***)- The frequency of the laser being used is not constant, but lies within a range belonging to the color of light. The frequency of light does not affect the results of the experiment and is controlled as the frequency fluctuates between a certain range of frequencies.

EXPECTED GRAPHS

The graphs being used are secondary sources, all from different sources. These graphs will be used to check the accuracy and precision of data collected and processed, and can also be used to correct errors in data collected. These graphs will also help in producing a better picture of how a general trend of intensity of light would look like, for all spectra of light.




Transmission (OD 0.1 - 0.6)
OD 0.1
OD 0.2
OD 0.3
OD 0.4
OD 0.5
OD 0.6
% Transmission
Wavelength (nm)
0
10
20
30
40
50
60
70
80
90
100
300
400
500
600
700
800
900
1000
1100


Absorptive ND Filters
OD 0.1
OD 0.15
OD 0.2
OD 0.3
OD 0.4
OD 0.5
OD 0.6
OD 0.7
OD 0.9
OD 1.0
OD 1.3
OD 1.5
OD 2.0
OD 2.5
OD 3.0
Transmission (%)
Wavelength (nm)
0
10
20
30
40
50
60
70
80
90
100
400
500
550
600
650
700
750

RAW DATA

1.1.1 - Red Laser Raw Data

Light Color	ND Value (ND)	Reading Before Polarization (Lux)	After polarization (Lux)
Red	2	8.84×10^4	1.74×10^4
Red	2	9.83×10^4	1.75×10^4
Red	2	7.21×10^4	1.47×10^4
Red	4	8.30×10^4	2.47×10^4
Red	4	6.12×10^4	1.41×10^4
Red	4	6.89×10^4	2.30×10^4
Red	1024	8.70×10^4	1.00×10^1
Red	1024	7.36×10^4	9.00×10^0
Red	1024	5.41×10^4	1.40×10^1
Red	2000	8.12×10^4	1.90×10^1
Red	2000	7.04×10^4	1.30×10^1
Red	2000	4.33×10^4	5.00×10^0

1.1.2 - Green Laser Raw Data

Light Color	ND Value (ND)	Reading Before Polarization (Lux)	After polarization (Lux)
Green	2	4.83×10^4	9.17×10^3
Green	2	2.78×10^4	2.99×10^3
Green	2	1.42×10^4	2.30×10^3
Green	4	1.30×10^5	1.24×10^4
Green	4	4.42×10^4	1.16×10^4
Green	4	5.27×10^4	1.27×10^4
Green	1024	1.09×10^5	3.90×10^1
Green	1024	5.59×10^4	4.70×10^1
Green	1024	5.35×10^4	4.00×10^1
Green	2000	4.86×10^4	4.40×10^1
Green	2000	4.90×10^4	5.10×10^1
Green	2000	4.73×10^4	4.40×10^1

1.1.3 - Violet Laser Raw Data

Light Color	ND Value (ND)	Reading Before Polarization (Lux)	After polarization (Lux)
Violet	2	4.83×10^4	4.75×10^3
Violet	2	4.89×10^4	1.76×10^4
Violet	2	4.83×10^4	4.71×10^3
Violet	4	5.12×10^4	4.35×10^3
Violet	4	4.80×10^4	1.76×10^4
Violet	4	5.03×10^4	1.34×10^4
Violet	1024	5.14×10^4	2.10×10^1
Violet	1024	4.80×10^4	1.90×10^1
Violet	1024	5.10×10^4	3.50×10^1
Violet	2000	4.83×10^4	4.50×10^1
Violet	2000	4.34×10^4	4.40×10^1
Violet	2000	5.03×10^4	4.10×10^1

PROCESSED DATA

The formula used was

$$T = \frac{I_f}{I_0}$$

Where $\boldsymbol{T}$ is the fractional transmittance, $\boldsymbol{I_0}$ is the intensity of light before polarization, and $\boldsymbol{I_f}$ is the intensity of light after polarization through the ND filter.

Key : *R = Red, G = Green, V = Violet*

1.2.1 - Red Laser Processed Data

Light Color	ND Value	Intensity Before Polarization (I_0)	Intensity After Polarization (I_f)	Fractional Transmittance (T)	Actual Fractional Transmittance for White Light	Average Fractional Transmittance (T)
R	2	8.84×10^4	1.74×10^4	1.97×10^{-1}	0.5	
R	2	9.83×10^4	1.75×10^4	1.78×10^{-1}	0.5	1.93×10^{-1}
R	2	7.21×10^4	1.47×10^4	2.03×10^{-1}	0.5	
R	4	8.30×10^4	2.47×10^4	2.98×10^{-1}	0.25	
R	4	6.12×10^4	1.41×10^4	2.30×10^{-1}	0.25	2.87×10^{-1}
R	4	6.89×10^4	2.30×10^4	3.35×10^{-1}	0.25	
R	1024	8.70×10^4	1.00×10^1	1.15×10^{-4}	0.001	
R	1024	7.36×10^4	9.00×10^0	1.22×10^{-4}	0.001	1.65×10^{-4}
R	1024	5.41×10^4	1.40×10^1	2.59×10^{-4}	0.001	
R	2000	8.12×10^4	1.90×10^1	2.34×10^{-4}	0.0005	
R	2000	7.04×10^4	1.30×10^1	1.85×10^{-4}	0.0005	1.78×10^{-4}
R	2000	4.33×10^4	5.00×10^0	1.15×10^{-4}	0.0005	

1.2.2 - Green Laser Processed Data

Light Color	ND Value	Intensity Before Polarization (I_0)	Intensity After Polarization (I_f)	Fractional Transmittance (T)	Actual Fractional Transmittance for White Light	Average Fractional Transmittance (T)
G	2	4.83×10^{4}	9.17×10^{3}	1.90×10^{-1}	0.5	
G	2	2.78×10^{4}	2.99×10^{3}	1.07×10^{-1}	0.5	1.53×10^{-1}
G	2	1.42×10^{4}	2.30×10^{3}	1.62×10^{-1}	0.5	
G	4	1.30×10^{5}	1.24×10^{4}	9.56×10^{-2}	0.25	
G	4	4.42×10^{4}	1.16×10^{4}	2.63×10^{-1}	0.25	2.00×10^{-1}
G	4	5.27×10^{4}	1.27×10^{4}	2.41×10^{-1}	0.25	
G	1024	1.09×10^{5}	3.90×10^{1}	3.58×10^{-4}	0.001	
G	1024	5.59×10^{4}	4.70×10^{1}	8.41×10^{-4}	0.001	6.49×10^{-4}
G	1024	5.35×10^{4}	4.00×10^{1}	7.48×10^{-4}	0.001	
G	2000	4.86×10^{4}	4.40×10^{1}	9.05×10^{-4}	0.0005	
G	2000	4.90×10^{4}	5.10×10^{1}	1.04×10^{-3}	0.0005	9.59×10^{-4}
G	2000	4.73×10^{4}	4.40×10^{1}	9.31×10^{-4}	0.0005	

1.2.3 - Violet Laser Processed Data

Light Color	ND Value	Intensity Before Polarization (I_0)	Intensity After Polarization (I_f)	Fractional Transmittance (T)	Actual Fractional Transmittance for White Light	Average Fractional Transmittance (T)
V	2	4.83×10^{4}	4.75×10^{3}	9.84×10^{-2}	0.5	
V	2	4.89×10^{4}	1.76×10^{4}	3.59×10^{-1}	0.5	1.85×10^{-1}
V	2	4.83×10^{4}	4.71×10^{3}	9.76×10^{-2}	0.5	
V	4	$5.12 \times 10^{4}4$	4.35×10^{3}	8.49×10^{-1}	0.25	
V	4	4.80×10^{4}	1.76×10^{4}	3.66×10^{-1}	0.25	2.39×10^{-1}
V	4	5.03×10^{4}	1.34×10^{4}	2.66×10^{-1}	0.25	
V	1024	5.14×10^{4}	2.10×10^{1}	4.08×10^{-4}	0.001	
V	1024	4.80×10^{4}	1.90×10^{1}	3.96×10^{-4}	0.001	4.97×10^{-4}
V	1024	5.10×10^{4}	3.50×10^{1}	6.87×10^{-4}	0.001	
V	2000	4.83×10^{4}	4.50×10^{1}	9.32×10^{-4}	0.0005	
V	2000	4.34×10^{4}	4.40×10^{1}	1.01×10^{-3}	0.0005	9.20×10^{-4}
V	2000	5.03×10^{4}	4.10×10^{1}	8.14×10^{-4}	0.0005	

GRAPHS

1.3.1 - Data for Figure (i)

ND Value	Red ~ 650 nm	Green ~ 530 nm	Violet ~ 480 nm
2	1.93×10^{-1}	1.53×10^{-1}	1.85×10^{-1}
4	2.87×10^{-1}	2.00×10^{-1}	2.39×10^{-1}
1000	1.65×10^{-4}	6.49×10^{-4}	4.97×10^{-4}
2000	1.78×10^{-4}	9.59×10^{-4}	9.20×10^{-4}

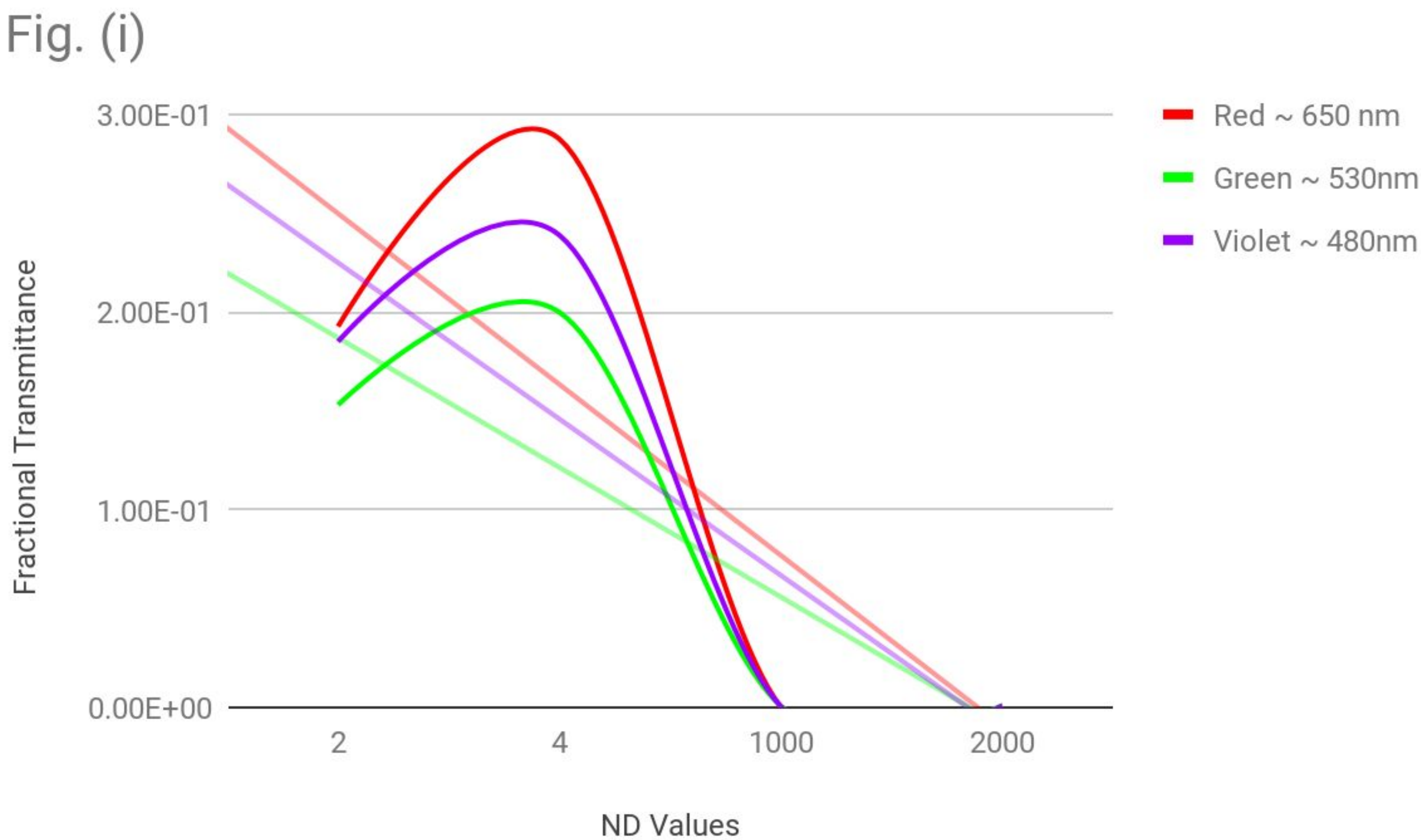


Fig. (i) is a graph where the optical density is plotted against the fractional transmittance for each wavelength of light, with the straight lines being the lines of best fit. This graph is plotted to show the difference in fractional transmittance and the trend each wavelength of light undergoes, when getting polarized.

1.3.2 - Data for Figure (ii)

Wavelength	2	4	1000	2000
480	1.85×10^{-1}	2.39×10^{-1}	4.97×10^{-4}	9.20×10^{-4}
530	1.53×10^{-1}	2.00×10^{-1}	6.49×10^{-4}	9.59×10^{-4}
650	1.93×10^{-1}	2.87×10^{-1}	1.65×10^{-4}	1.78×10^{-4}

Fig. (ii)

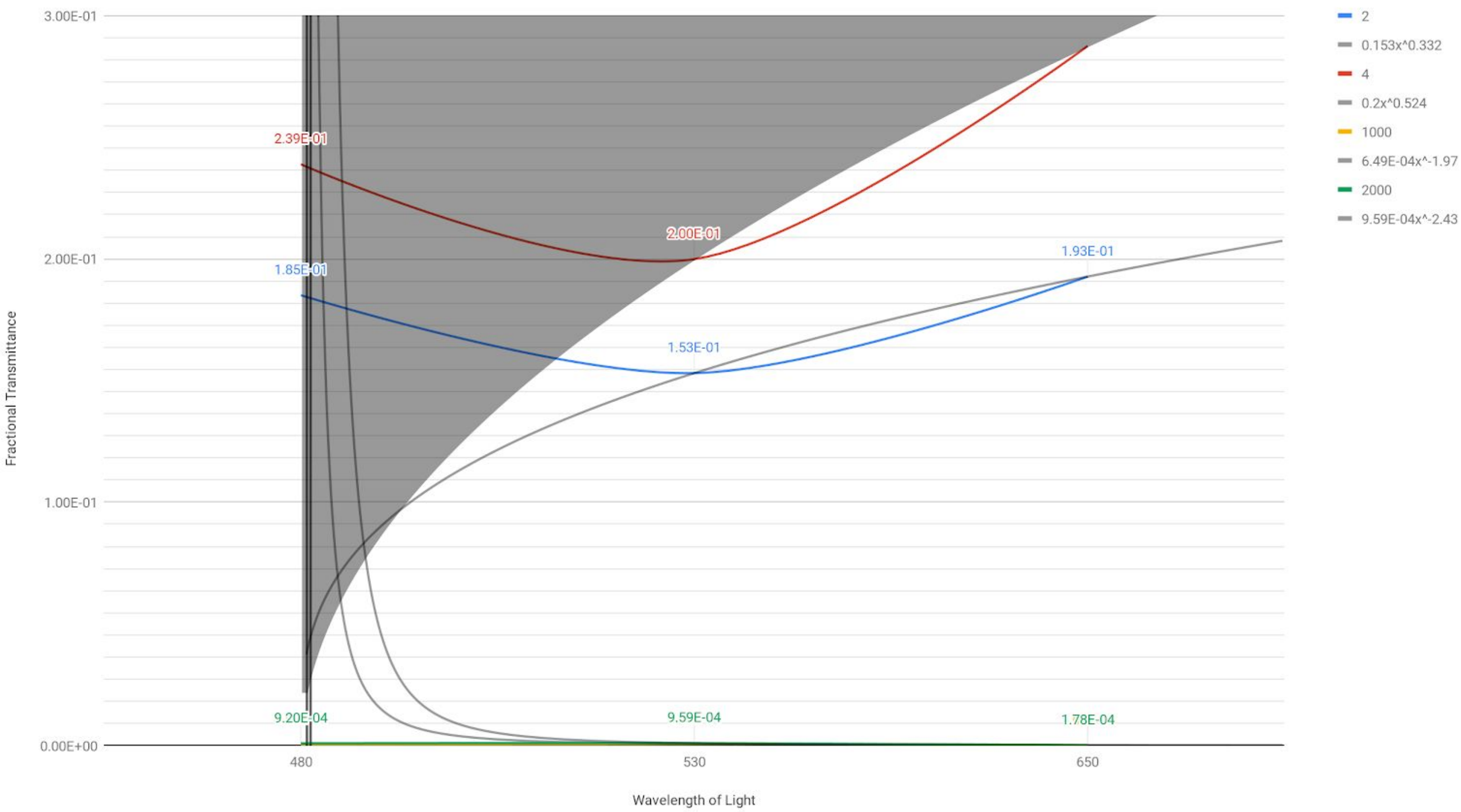


Fig. (ii) is a graph where the wavelength of light is plotted against fractional transmittance, and the curves are one optical density each. This graph was plotted so that a comparison could be made between the expected graphs, a possible integrated graph, from this graph, and this graph itself, and to see how the trend between the wavelength of light and fractional transmittance due to polarization works.

ANALYSIS OF PROCESSED DATA AND GRAPHS

Looking at Figure (ii), it can be inferred that as the optical density increases, the rate of change of the fractional transmittance decreases, as wavelength increases. However, the data does not show any similarity to that of the expected graphs.

The reason for that could be the irregularity in the readings taken for the green laser, were value before polarization were very random in terms of range, whereas the red and violet lasers had smaller ranges and standard deviation in terms of data. Due to the irregularity of the readings from the green laser, the shape of the curve differs from the ones in the expected graphs, from secondary sources.

Also, the values for transmitted fraction of monochromatic light varied vastly compared to that of white light. Red light was the closest to white light, although there was still a marginal difference in the fractional transmittance, for ND2 - Red being 0.2 and White light being 0.5. But, as the optical density increased (i.e. ND value increased), the values for fractional transmittance of light of shorter wavelength was closer to that of white light, where violet light's fractional transmittance was the closest to that of white light, and vice versa for red. This shows a sort of reversed relationship between the wavelength and optical density, whose graph looks similar to the lines of best fit of (2) & (4) from Fig.(ii), which would look like the function :

This rate of change, however does not show when interpreting curves with smaller values, such as (1000) & (2000) from Fig. (ii).

EVALUATION

One of the largest reasons for errors in this study are due to the green laser pointer that was used. It was a laser pointer but had a prism attached to it to disperse light in various patterns. The prism was removed to conduct the experiment, and the simple removal of this object could have result in the irregularity of results, in the case of the green laser pointer.

The raw data does not have any uncertainties due to their small value. After the calculation of fractional transmittance, the uncertainty is beyond negligible, as the least count of this digital luxmeter was 1 lux, with readings in the ten thousands. This is also why there are no error bars in Fig.(i) and Fig.(ii).

The lux-meter also seemed to have some form of systematic error, as although there was a lot of ambient light, the value shown on the meter was still zero at the start of each reading. While the experiment was being conducted, as the ND filter was variable, it might have rotated while I was holding it, which could have been the result of some random errors in the cases of higher optical density, as the filter can provide another level of optical density, after ND2000. Due to the larger optical densities being large values, with small intervals, even turning the filter by a few degrees, could have affected readings.

My computer was a source of ambient light in the room where this experiment was conducted which also could have possibly resulted in very small errors, but could have affected the amount of light absorbed by the luxmeter, when taking reading, due to black body radiation, which could have resulted in some random errors, in terms of fluctuating value, in the same wavelength of light, which could have affected how precise the data was.

CONCLUSION

Based on the trends found in Fig.(i), it can be shown that there is a uniform decrease in the fractional transmittance of light, when shifting from red light to violet light. On the other hand, green light had the lowest values for fractional transmittance, being lower than oth red and violet, and a possible explanation for this is that the laser used for green light was a pattern laser, with the pattern cover removed, which could have affected the readings for the fractional transmittance. But, since that the trend is general from red to violet, which are at either end of the visible light spectrum, I am coming to the conclusion that optical density does affect different wavelengths of light at different levels, resulting in varying levels of fractional transmittance of light.

The data shows that as the optical density affects light of shorter wavelengths more than longer wavelengths, meaning that electromagnetic radiation such as ultraviolet light, if polarized would be less intense if infrared light of the same intensity were to pass through a polarizer of the same optical density.

Fractional Transmittance is directly proportional to the wavelength of light.

$$T \propto \lambda$$

FURTHER APPLICATION

There are several applications for this concept in the real world. Polarization actively takes place in nature. Water polarizes light that enters it, to later be absorbed by aquatic plants such as Eel grass, which is an important part of the aquatic ecosystem as it supports the lives of many fish and shellfish. Hydroponics is a type of farming that uses only water, nutrients and light to grow plants. Thus, to maximize the growth of these plants, they must receive the maximum amount of electromagnetic radiation possible, which can be found by using the trend found in this paper.

Another application is in the reduce ultraviolet light. A specific type of UV light, known as UV-C radiation is harmful to the human body, penetrating the skin, and can cause skin cancer, by mutating cells in the body, making them cancerous. To prevent this, windows, curtains, or blinds could be covered with a thin polaroid, which could reduce the intensity and severity of that UV-C radiation, which could possibly help prevent the development of skin cancer and damage of skin cells.

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