International Baccalaureate
Extended Essay

Efficiency of Optical Fiber Cables Due to the Angle of Incidence

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Physics

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Abstract

The scope of this experiment is based on figuring out the answer of the following question: “What is the effect of angle of incidence for the light passing from air to *core* on the efficiency of optical fiber cables?” The term “efficiency” is leaning on the difference between output intensities of laser. A helium-neon continuous laser is used throughout the investigation. This type of laser has relatively low energy compared to other lasers such as Nd:YAG lasers with 110 pulse per second with 1mJ of power at each pulse. which reduces the risk of experiment accidents for instance damaging optical fiber cable, intensity spectrometer or other equipment in the laboratory. Since the single-mode fiber’s diameter is very small (9 microns), it was nearly impossible to align the ray of laser light and cable every time the angle changes. Therefore, a high-resolution mirror is used to adjust the angles if incidence and one end of the cable is stabilized on a platform that enables only 1-dimensional motion. Rotating the mirror on a fixed change the angle of reflection, this caused differences in angles if incidence from air to *core* to optical fiber cable. The signal is traveled along the *core* of cable, constantly bouncing from *cladding*, which has smaller refractive index to apply the principal called total internal reflection. The other end of the optical fiber cable is connected to an intensity spectrometer to observe the changes in the output intensity as the angle if incidence changes. The output intensity remained same until a certain angle, which is the critical angle, then it begun to decrease as the angle of incidence for the light passing from the air to core of the optical fiber increases.

Introduction

The scope of work is to test the phenomena total internal reflection on daily life. Nowadays, most of the communication signals such as Internet are transferred by optical fiber cables using the reflection and refraction principles of optics. This method of transferring data is very fast and efficient. However, some external factors may affect the efficiency of transport such as loss of signals because the rays with incident angles smaller than the critical angle cannot not reflect, instead they refract and pass to *cladding.* Another cause that decreases efficiency is the energy of the laser travels through the cable. If a laser beam with high power that the materials of core and cladding cannot withstand is sent to optical fiber cable, the photons carrying excessive energy may degrade the properties of materials the core and cladding are made of and change the ability to reflect the light negatively. Also this high energy may damage the devices connected to optical fiber cables. The first objective of this piece of work is to find the appropriate power of laser to carry light with the highest energy in the same amount of time as much as possible without causing any damage neither cable nor device connected to the end of the cable.

Background Information and Literature

What is Light?

Light is a simple name for electromagnetic radiation.
Light, electromagnetic radiation behaves as both particles and waves. Electromagnetic waves have amplitude, which means the brightness of light, a wavelength, constant distance between two crests, which means the color of light and the direction that the waves oscillate is called polarization. According to modern quantum theory, light consists of photons, which are packets of energy that travels at light speed at vacuum. In particles view of view, number of photons determines the brightness and energy contained in each photon refers to the color of light.

What is Photon?

It is be possible to describe a photon as the carrier of electromagnetic energy.

Photon is the elementary particle, quanta of light and all other electromagnetic waves. Also, it is the force for electromagnetic force. Photon has no rest mass, therefore its effect can be observed for both long and short distances.

The property of light that can interact with long distances is the beginning of the idea that information can be traveled long distances by optical fiber cables.[1]

Photons are always in motion and, in a vacuum, have a constant speed of light to all observers, at the vacuum speed of light.[2]

What is Refraction and Total Internal Reflection?

Refraction is bending of light when it passes from medium with different indices (where the speed of light is different). When light passes from a medium with low index (high speed) to high index (low index) the ray of the light bends towards the normal to boundary. The amount of bending depends on the indices of the mediums.

Snell's Law explains the amount of bending quantitatively.

Derivation of the Snell's Law is as the following steps

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[1] http://en.wikipedia.org/wiki/Photon

[2] http://physics.about.com/od/lightoptics/f/photon.htm

1. Time for the trip equals distance traveled divided by the speed.

$$T = \frac{d_1}{v_1} + \frac{d_2}{v_2}$$

2. Using the Pythagorean theorem from Euclidean Geometry we see that

$$\frac{d_1}{v_1} = \frac{\sqrt{x^2 + a^2}}{v_1} \quad \text{and} \quad \frac{d_2}{v_2} = \frac{\sqrt{b^2 + (l - x)^2}}{v_2}$$

3. Substituting this result into equation (1) we get

$$T = \frac{\sqrt{x^2 + a^2}}{v_1} + \frac{\sqrt{b^2 + (l - x)^2}}{v_2}$$

4. To minimize the transit time, we take the derivative with respect to the variable x and set it equal to zero:

$$\frac{dT}{dx} = \frac{x}{v_1\sqrt{x^2 + a^2}} + \frac{-(l - x)}{v_2\sqrt{(l - x)^2 + b^2}} = 0$$

5. After careful examination the above equation we see that it is nothing but

$$\frac{dT}{dx} = \frac{\sin\theta_1}{v_1} - \frac{\sin\theta_2}{v_2} = 0$$

6. This leads to

$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2}$$

7. Substituting $\frac{n_1}{c}$ for $\frac{1}{v_1}$ and $\frac{n_2}{c}$ for $\frac{1}{v_2}$ we get

$$\frac{n_1}{c}\sin\theta_1 = \frac{n_2}{c}\sin\theta_2$$

8. Multiplying through by c gives us our result

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

However, when light is travelling through a medium with high index to low index. There are 3 possibilities: light can bend away from the normal to boundary, light can travel along the boundary in parallel and light can totally reflect. To distinguish these 3 possibilities, it is necessary t become familiar with the term “critical angle”. “Critical angle is defined as the angle of incidence that provides an angle of refraction of 90-degrees.”[3]

According to Snell’s Law:

$$n_1 * \sin\theta_1 - n_2 * \sin\theta_2$$

$$n_1 * \sin\theta_{crtitical} = n_2 * \sin 90$$

$$\sin\theta_{crtitical} = \frac{n_2}{n_1}$$

$$\theta_{critical} = \sin^{-1}\frac{n_2}{n_1}$$

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[3] http://www.physicsclassroom.com/class/refrn/u14l3c.cfm

Therefore, lights with lower incident angle than critical angle will refract according to Snell's Law and lights with greater incident angel than critical angle will totally reflect since the sinus function has a range between [-1,1]. It cannot be greater than 1.

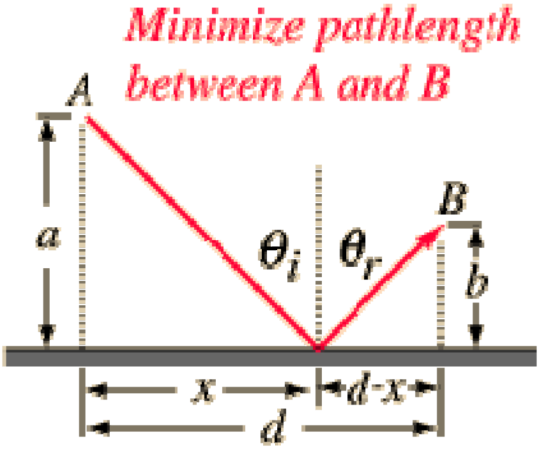
Total internal Reflection is phenomenon when the light strikes a medium with a lower refractive index then the medium the light is originated from, incident angle of light, angle of the ray with respect to the normal to boundary is greater than the critical angle, light cannot be refracted to the next medium. Instead it is entirely reflected to the medium it is originated from.

To give an example, a man standing near the lake and looking to water can see through and see the fish rock etc. beneath the surface of water(a little distorted because of the refraction). However, when he glances to further points of lake, it is more unlikely to see through the water. This time he can see the trees, mountain etc. at the opposite shore. This is total internal reflection

Reflection can be defined as the change in direction of wavefront at an interface between two different mediums so that the wavefront can return the medium it is originated from.

According the Fermat's Equation:

Light follows the path of least time. The law of reflection can be derived from this principle as follows:



The pathlength(L) from A to B is

$$L = \sqrt{a^2 + x^2} + \sqrt{b^2 + (d - x)^2}$$

$$\frac{d_L}{d_x} = \frac{1}{2}\frac{2x}{\sqrt{a^2 + x^2}} + \frac{1}{2}\frac{2(d - x)(-1)}{\sqrt{b^2 + (d - x)^2}} = 0$$

This reduces to $\frac{x}{\sqrt{a^2+x^2}} = \frac{(d-x)}{\sqrt{b^2+(d-x)^2}} = 0$

which is $\sin\theta_i = \sin\theta_r$

$$\theta_i = \theta_r$$

Therefore, according to reflection law, incident angle and the reflected angle must be equal to each other. [4]

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[4] http://en.wikipedia.org/wiki/Snell's_law

Optical Fiber Cables

An optical fiber consists of one or more optical fibers. Generally an optical fiber contains three layers. The internal layer is called *core* where the light travels, middle layer is called *cladding* which provides the cable reflection ability and the outer most layer is coated with plastic. The outer most layer has no optical waveguide properties. The purpose of this plastic is to protect the inner two layers from mechanical damages.

Due to the difference in refractive indices of core and cladding, refraction and reflection occurs.
"The composition of the cladding glass relative to the core glass determines the fiber's ability to reflect light. Creating a higher refractive index in the core of the glass than in the surrounding cladding glass, creating a "waveguide", usually causes that reflection. The refractive index of the core is increased by slightly modifying the composition of the core glass, generally by adding small amounts of a dopant. Alternatively, reducing the refractive index of the cladding using different dopants can create the waveguide. "

Working Principle of Fiber Optic Cables

The working principle of optical fibers is based on total internal reflection. Light reflects or refracts depending on the angle incident angle, the angle that strikes the surface of another medium.

This principle is the hearth of this investigation. Controlling the incident angles that the light waves are transmitted makes it possible to observe the efficiency of the signal that how much of it reaches the destination. Lightwaves travel through the core of the optical fiber and due to the difference in refractive indices between the materials of core and cladding it reaches its destination by being reflected continuously within the core."[5]

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[5] http://www.imedea.uib.es/~salvador/coms_optiques/addicional/Corning/fiber_optic.pdf

Design

Research Question

How does the power of the changes out of the fiber optic cable according to the initial power under stable conditions such as constant wavelength of light, temperature and constant type of material that cable made?

Hypothesis

Increasing the angle of incidence for the light passing through the air to core of the light to the cable is going to decrease the efficiency because; total internal reflection occurs at the angles greater than the critical angle, for the angle values smaller than critical results in both refraction and reflection. Increasing the angle of incidence from the light passing through air to core is going to cause a decrease in the angle of incidence for the light travelling within the optical fiber cable and this decrease will cause a bigger portion of light to be refracted to the core, which means data loss.[6]

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[6] http://www.ciscopress.com/articles/article.asp?p=170740&seqNum=3

Variables

Dependent Variable:

1. Output power of the ray

Independent Variables:

1. Entrance angle of the ray to the fiber optic cable

Controlled Variables:

1. Wavelength of the light
2. Type of laser source
3. Degree of natural density filter
4. Distance between the fiber optic cable and the laser source
5. Temperature of the room
6. Diameter of the glass in fiber optic cable
7. Length of the fiber optic cable
8. Made up material of fiber optic cable
9. Air density
10. Incident power of the ray

Materials

1. Helium-Neon Continuous Laser Source with 633 nm wavelength and 5mW power
2. 1 meter long fiber optic cable
3. Second degree Natural Density Filter
4. Infrared cards for alignment
5. Intensity spectrum analyzer
6. A protractor in order to adjust the entrance angel
7. Off-Axis Parabolic Protected Gold Coating Mirror
8. Cable stabilizer
9. A 1-dimentional stage
10. Power meter

Diagram of Experiment Setup

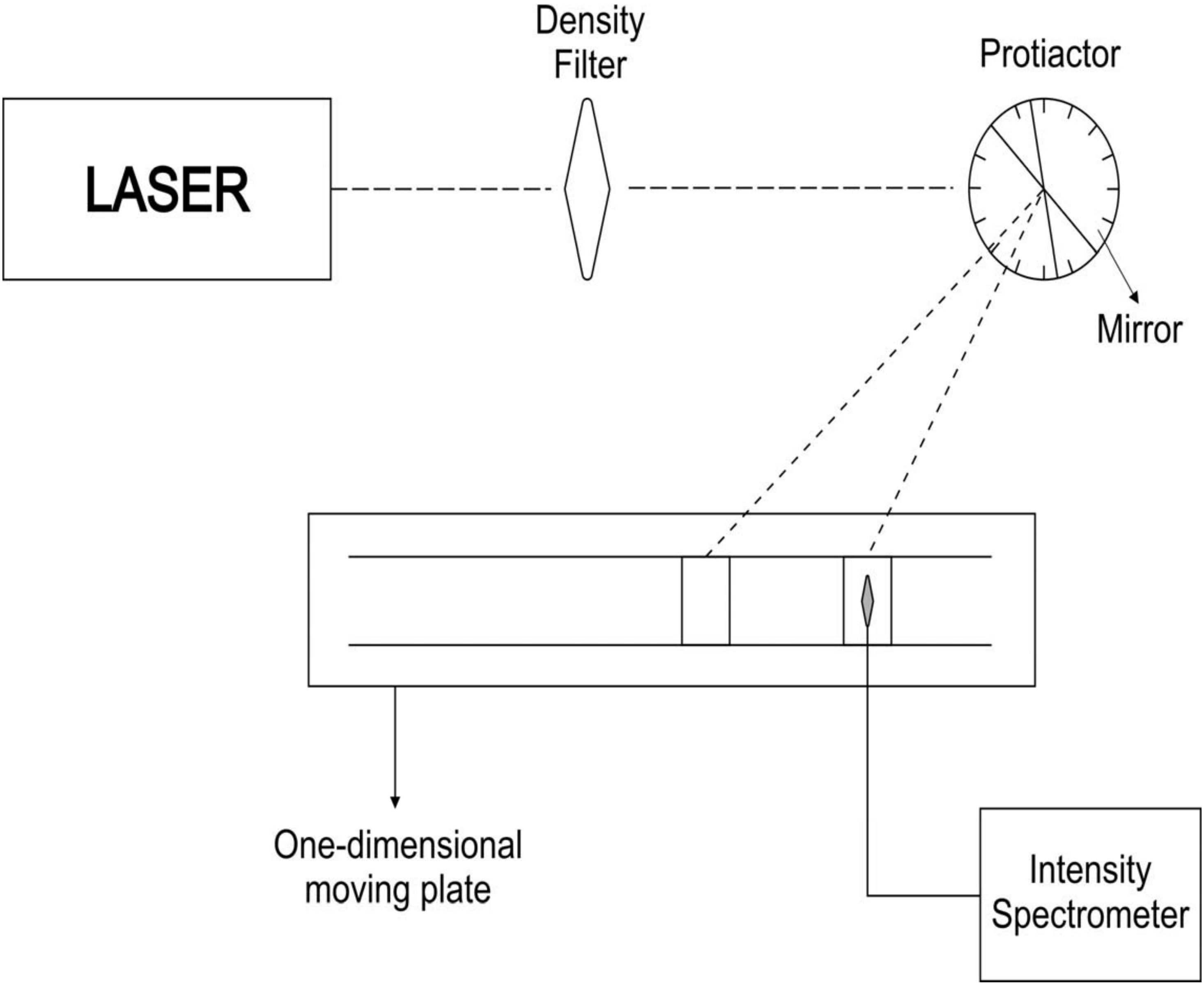


Figure 1

Measuring Intensity

As can be seen from the diagram above, the laser source placed and stabilized at a single point on the table in order to get more accurate angles. A mirror is placed on a protractor for measurement of the entrance angle of the ray to the fiber optical cable. The cable is stabilized on a 1-dimensional stage. The purpose of the stage is to move the cable on a single line without changing the entrance angle. This step necessary because as the mirror is rotated on protractor, laser ray reflected by the mirror changes its direction and cuts the line that the cable travels on a different point. In order to move the entrance of the optical fiber to those particular points, a 1-dimensional stage is used.

First angle of incidence was 0o. The laser is reflected directly through the optical fiber. And the output intensity is measured by intensity spectrometer analyzer. Since, the angle between the surface of the fiber and the ray is 90o, there was no refraction. After first measurement, the mirror rotated 1o, which caused a change in the direction of the reflected ray 2o. The reason of the double change in the angle is both the surface and normal of the surface rotated. Since the direction of the reflected ray changes, the ray could not be able to enter the cable. Therefore, the cable is moved along the stage. A wheel provides the motion of the stage. One round of the wheel corresponds to 1 micron, which makes the alignment of entrance of cable and the ray very accurate. Unlikely the first measurement, there was refraction occurred because of the difference in refractive indices of core of optical fiber and the air. The reflection or refraction in optical fiber cable occurred with different angles due to this refraction due to the refraction occurred when the ray transferred to core of the cable from the air. Required calculations are shown in “Calculation for Reflection/ Refraction Angles” section of the essay. These steps are repeated several times until it the length of 1-dimensional stage limits the investigation. During the investigation, it is observed that the output intensity remained same until a certain angle value, which created the critical angle inside the cable and started to decrease as this angle is exceeded.

Data Collection and Processing

Raw Data Table

Rotation Angel of Mirror (±0.1)	Wavelength of Laser Beam (±0.001) nm	Distance Between Laser Source and Mirror (±0.01) cm	Distance Between Mirror and Fiber Optic Cable (±0.01) cm	Power of Incident Ray (±0.001)mW	Power of Ray after NDF (±0.001)µW	Frequency of Photon Release	Diameter of Fiber optic Cable(±0.001) µm	Input Intensity of Light (±400)cd	Output Intensity of Light (±0.400)cd
0.0	633.000	121.00	4.63	5.126	73.320	Continuous	9.230	15500	15500
1.0	633.000	121.00	4.63	5.849	73.785	Continuous	9.230	15500	15500
2.0	633.000	121.00	4.63	5.829	73.772	Continuous	9.230	15500	15500
3.0	633.000	121.00	4.63	5.384	73.457	Continuous	9.230	15500	15500
4.0	633.000	121.00	4.63	5.918	73.892	Continuous	9.230	15500	15500
5.0	633.000	121.00	4.63	5.280	73.437	Continuous	9.230	15500	15500
6.0	633.000	121.00	4.63	4.978	73.150	Continuous	9.230	15500	15500
7.0	633.000	121.00	4.63	5.723	73.633	Continuous	9.230	15500	15500
8.0	633.000	121.00	4.63	5.111	73.210	Continuous	9.230	15500	15500
9.0	633.000	121.00	4.63	5.096	73.168	Continuous	9.230	15500	15500
10.0	633.000	121.00	4.63	4.983	73.019	Continuous	9.230	15500	15200
11.0	633.000	121.00	4.63	5.439	73.692	Continuous	9.230	15500	14700
12.0	633.000	121.00	4.63	5.826	73.850	Continuous	9.230	15500	12100
13.0	633.000	121.00	4.63	5.528	73.629	Continuous	9.230	15500	10200
14.0	633.000	121.00	4.63	5.271	73.381	Continuous	9.230	15500	8700
15.0	633.000	121.00	4.63	5.283	73.472	Continuous	9.230	15500	7500
16.0	633.000	121.00	4.63	5.582	73.592	Continuous	9.230	15500	6700
17.0	633.000	121.00	4.63	5.394	73.483	Continuous	9.230	15500	6200
18.0	633.000	121.00	4.63	5.716	73.729	Continuous	9.230	15500	5800
19.0	633.000	121.00	4.63	5.689	73.210	Continuous	9.230	15500	5000
20.0	633.000	121.00	4.63	5.798	73.168	Continuous	9.230	15500	4400
21.0	633.000	121.00	4.63	5.394	73.019	Continuous	9.230	15500	4000

Table 1 shows the change in input and output intensities of the light according to the change in rotation angle of the mirror that causes differences in incidence of angle for the light passing through the air to core. Power of ray is reduced by a Natural Density Filter and the power values of laser ray before and after the NDF also shown in the Table 1.

Calculation for Angle of Incidence of Reflection/Refraction within Cable

The angle of incidence for the light passing from air to core changed by changing the direction of reflected ray by rotating the mirror on a stable protractor. For the first angle, which is 0.0°, no refraction has occurred. However, for the next angles, the light changed its direction as it penetrates the optical fiber because of the difference in refractive indices of the material of core and the air.

According to incidence angle between air and the core, laser ray it follows 3 different paths. As seen in the next page *Figure 3,* after the first refraction, if the sum of angle of refraction and the critical angle is 90 degrees, the ray travels along the surface between cladding and core. Let's name this angle of incidence for the light passing through the air to core that leads to critical angle inside the optical fiber as *"Specific Angle"* The rays that makes smaller angle than the *Specific Angle* leads a greater angle than the critical angle between core and cladding, there for total internal reflection occurs. Path of the rays that makes total internal reflection is shown in *Figure 4.* As shown in the *Figure 2* at the next page, angles greater than the *Specific Angle* lead to a smaller angle than critical angle and refraction occurs. This refraction is the cause of data loss, reduction of the efficiency.

According to incidence angle between air and the core, laser ray it follows 3 different paths:

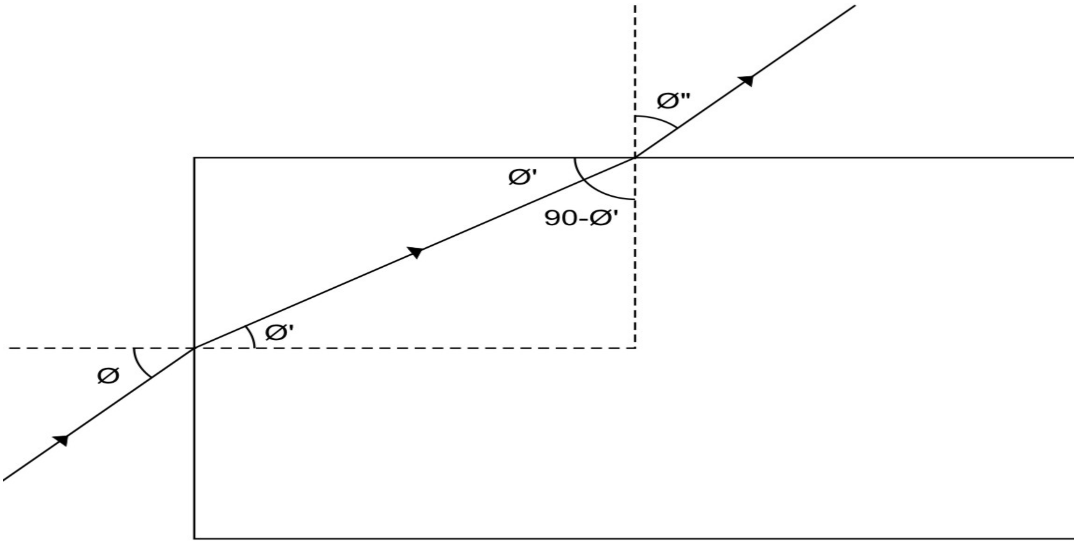


Figure 2

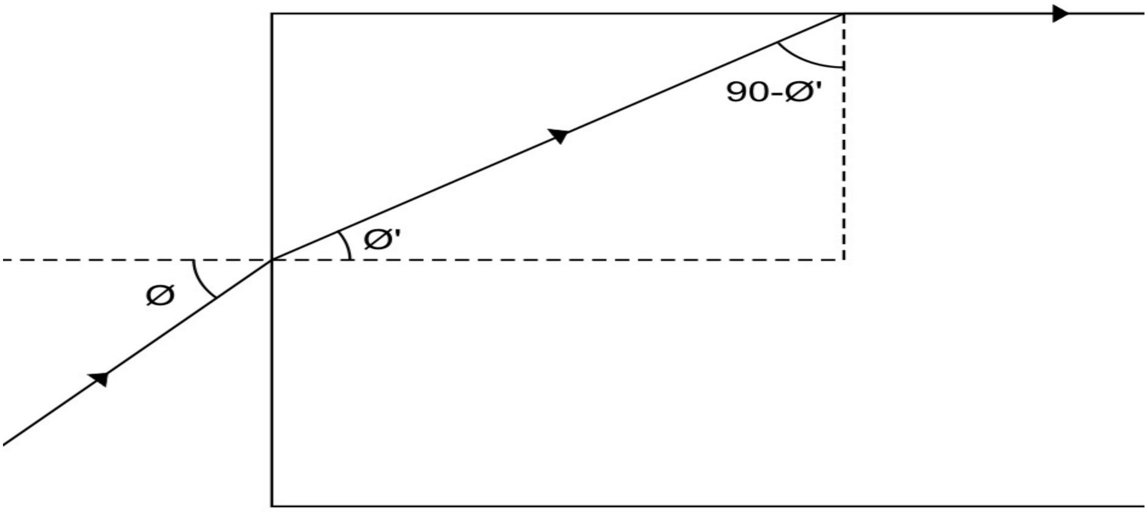


Figure 3

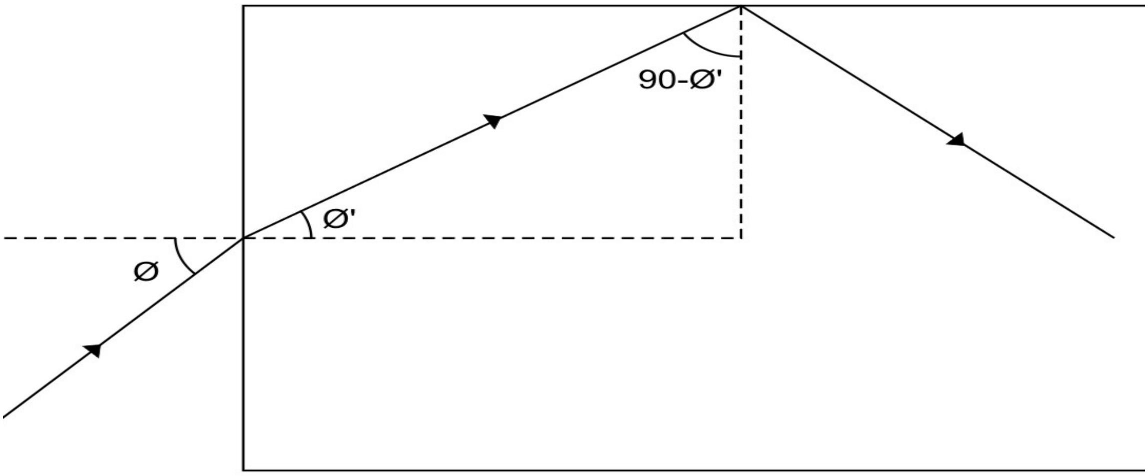


Figure 4

Refractive indices of air, core and the cladding are shown below. The required equation is derived by using Snell's Law, refractive index values and basic trigonometry.

$n_{air} = 1 \qquad n_{core} = 1.55 \qquad n_{cladding} = 1.50$

$n_{air} * \sin 2\theta = \sin\theta' * n_{core}$

$$\sin\theta' = \frac{\sin 2\theta}{1.55}$$

$$\theta' = \sin^{-1}\left(\frac{\sin 2\theta}{1.55}\right)$$

$\theta_R = 90 - \theta'$

For the first refraction, required calculations for calculating the angle of incidence inside the core (incident angle of refraction) is shown below.

$\theta = 1°$

$$\theta' = \sin^{-1}\left(\frac{\sin 2\theta}{1.55}\right)$$

$$\theta' = \sin^{-1}\left(\frac{\sin 2}{1.55}\right)$$

$\theta' = 1.29$

$\theta_R = 90 - \theta' = 88.71$

Theoretical Value of Critical Angle:

$$\sin(90-\theta') * n_{core} = \sin 90 * n_{cladding}$$

$$\sin(90-\theta') = \frac{1.50}{1.55}$$

$$90-\theta' = \sin^{-1}(\frac{1.50}{1.55})$$

$$90-\theta' = 75.41$$

For the uncertainty:

The refractive indices of core and the cladding is 1.55 and 1.50 respectively. These values are not measured by myself but by the company that produces the cable instead. However, it is not an exact measurement so both values have an uncertainty of ±0.01.

Smallest value of critical angle:

$$\sin(90-\theta')*n_{core} = \sin 90 * n_{cladding}$$

$$\sin(90-\theta') = \frac{1.49}{1.56}$$

$$90-\theta' = \sin^{-1}(\frac{1.49}{1.56})$$

$$90-\theta' = 72.77$$

Highest value of critical angle:

$$\sin(90-\theta')*n_{core} = \sin 90 * n_{cladding}$$

$$\sin(90-\theta') = \frac{1.51}{1.54}$$

$$90-\theta' = \sin^{-1}(\frac{1.51}{1.54})$$

$$90-\theta' = 78.67$$

Deviations are

$78.67 - 75.4074 =$ +3.26 and

$72.77 - 75.40 = \ -2.63$

Uncertainty is

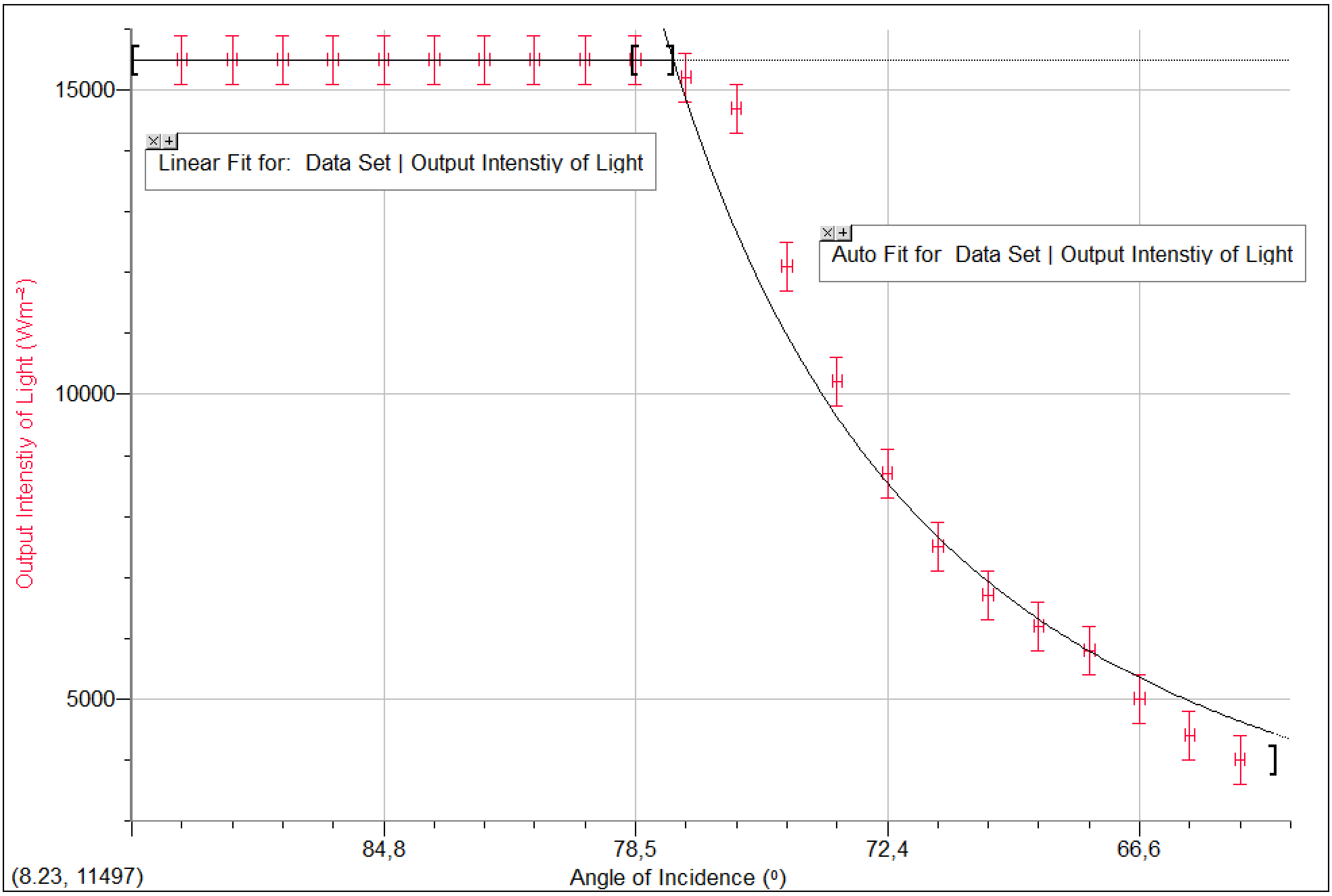
$$\frac{3.26+2.63}{2} = 2.95$$

Critical angle = 75.41 ± 2.95

Processed Data Table

Rotation Angle of Mirror (±0.1)	Rotation Angle of Reflected Ray (±0.1)	Angle of Incidence (Reflection/Refraction) Inside the *core* (±0.1)
1.0	2.0	88.7
2.0	4.0	87.4
3.0	6.0	86.1
4.0	8.0	84.8
5.0	10.0	83.6
6.0	12.0	82.3
7.0	14.0	81.0
8.0	16.0	79.8
9.0	18.0	78.5
10.0	20.0	77.3
11.0	22.0	76.0
12.0	24.0	74.8
13.0	26.0	73.6
14.0	28.0	72.4
15.0	30.0	71.2
16.0	32.0	70.0
17.0	34.0	68.9
18.0	36.0	67.7
19.0	38.0	66.6
20.0	40.0	66.6
21.0	42.0	64.4

Table 2 shows calculated values of angle of incidence of refraction/reflection inside the core. The equation shown above is used to calculate these angles.



Graph 1 shows the change in output intensity of light as the incident angle of refraction/ reflection changed by rotating the mirror and altering the angle of incident for the light passing through air to core.

In the graph drawn, 2 distinct patterns are formed. There is a critical angle value, which is 77.3°, that separates those two patterns. Before the critical value, the output intensity of light is constant at 15500 Wm^{-2}. After that an exponential graph that indicates an inverse relation in observed.

Conclusion & Evaluation

This experiment is carried out to find out how the output intensity of light changes according to the angle of incidence for the light passing through the air to core of the optical fiber. This change in angle affected the incident angle of reflections or refractions inside the cable that leads to some data loss. The primary scope of this work is to investigate the amount of lost data in the cladding due to refractions. However, through the experiment, the critical angle of the optical fiber cable is also tested.

At the end of the experiment *Graph 1* (output intensity of light vs. angle of incidence of refraction/reflection) is sketched. According to graph, the output intensity stays constant at 15500 Wm^{-2} until 77.3°, which is critical angle. After that, intensity started to decrease. The exponential relation between the output intensity of light and the incident angle is shown in the graph. The reason for 2 different patterns is the formations of reflections and refractions according the incident angle. As explained in the *Background Information and Literature* part, for the angles greater than the critical angle, total internal reflection has occurred. That means all of the rays are reflected back to the core and this process is repeated during its travel in the optical fiber cable. For the exact angle of critical angle, the laser ray travelled along the line between the core and the cladding. Angles smaller than the critical angle caused some of the datas to be lost because of refractions. for the angles smaller than the critical angle some of the rays are refracted into the cladding caused data loss. As the angle gets smaller, the refracted portion of the ray is increased, which lead to greater data loss. As a result of the experiment, as can be seen from the graph, the hypothesis came to be true.

The line and the curve touch most of the error bars except 4. Depending on this information, it is possible to say that the experiment was slightly precise.

The calculated critical angle by using the refractive indices of core and the cladding was 75.41 ± 2.95 °. The experimental value is 77.3 °. The experimental value is in the uncertainty range of the calculated value. Percentage derivation is

$$\frac{77.3-75.41}{75.41}*100=\%2{,}51$$

This information indicates that the experiment was accurate.

The pattern of results obtained from the experiment is as expected. However there was some systematic and random errors.

At the very beginning of the experiment, it was really difficult to align the laser with optical fiber cable since both thicknesses of the ray and the entrance of angle is too small. The laser source is moved in micron level to adjust the laser ray to be fit into the optical fiber but it is possible that not all of the light is penetrated into the cable.

A glorified, high-resolution mirror is used but it is possible that not all of the rays are reflected but some of them are refracted and lost in the material behind the mirror.

The laser source was producing high-powered photons that have a power of approximately 5mW. It is a really high value for intensity spectrometer that disables its capability of measuring the intensity. That much power disrupts its sensors. Therefore a filter used to reduce its power. Depending on the angle of incidence that the ray comes to the filter and the sphericity of the filter, the filter may behave as a lens and the rays can be converged or diverged. This change in directions may cause some derivations in the measurements because it changes the angles of incidence, which results in different portions of ray to be refracted or reflected.

As shown in the raw data table, the incident power of each photon radiated from the laser is not exactly the same. There are slight differences but it may affect the output intensity results and cause some errors because in order to investigate one variable, output intensity is the dependent variable for this experiment, the other variables must be kept constant such as input intensity.

The mirror is rotated with small angles as much as possible. The difference in each rotation is 1^o. However, as shown in the calculations, this small change in angle resulted in greater changes in incident angles of refraction/reflection. The datas could not be taken in regular intervals. The derivation of the critical angle can be result of this error. Only specific values, not the whole interval could be investigated.

As mentioned previously it was very challenging to align the laser ray and the optical fiber. Every rotation in mirror changed the direction of the ray and the ray cut the line of 1-dimensial stage at a different point. Therefore, stage moved for each measurement and required new alignment. Each alignment might not be perfect and caused different amounts of data loss even before it penetrates to the cable.

One of the limitations of the experiment was the length of the 1-dimensional stage. If it was longer it would be possible to take more measurements to identify the pattern more correctly.

For better alignments, a cable with a wider entrance or some computer assistance could be used. Little light censors can be put around the cable. If they detect a light, they would send a single to the computer and computer would rotate the ray a little bit more or less. However, also this improvement would not provide perfect alignment and it will cost more.

One important improvement would be to use a laser source with radiating photons with more stable power. Same as the previous improvement, it will be much more expensive and can not guarantee perfectly matched power at each radiation.