ON THE USE OF SCINTILLATING FIBERS TO

CONCENTRATE SOLAR LIGHT

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Electrical and Computer Engineering

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ABSTRACT

Optical fibers are a recently new research and the potential use for these fibers has only begun to emerge. Only type of fiber in particular is the scintillating fiber. It is cheaply and readily made out of plastic polymer materials and has great prospective for wave guiding. Due to the newborn nature of these fibers little research is known about their light generated current in comparison to their color, length, or radius. The current output was measured for the above variables using a silicon photo detector or solar cell along with a multi-meter that measured current in micro amps. These variables were manipulated and it was observed that each of the variables plays a significant role in the amount of light generated current that was produced. Knowing the absorption lengths of the fibers, and components that affect their output, allows for further research into how the fibers can be used in engineering mechanisms, specifically in conjuncture with solar cells.

Chapter 1

INTRODUCTION

1.1 Introduction to Solar Energy

With the growing population and the depletion of expendable energy sources such as fossil fuels it is of great concern to supplement this loss with alternate renewable energy sources. Solar energy is defined as the radiant energy emitted by the sun that is then collected, by means such as plant leaves, a pool of water, solar panel, and a multitude of other mechanisms.

The amount of energy reaching the surface of the earth every hour is greater than the amount of energy needed by the world's population over an entire year. It sustains all forms of life on the planet and it offers the largest energy sources viable for use by humans. Plants directly convert solar radiation in to energy by utilizing the photosynthesis process within the chlorophyll. The process also helps maintain a healthy level of oxygen on earth. Therefore solar energy is the number one reason that humans can survive. There are also many other ways that the solar energy is used in today's world. It can be harnessed as heat for solar hot water heaters, or the radiation can be directly converted to heat to cook food or heat things such as swimming pools or houses.

1.2 Introduction to Photovoltaics

Harnessing the power of the sun has been an ongoing battle for scientist all over the world. Over the past few decades researchers have begun harnessing the suns solar radiation and have been able to directly convert that to electrical power using solar cells. However there is a tradeoff between cost and efficiency for research based, and commercial manufactured photovoltaic systems.

Currently lab tested photovoltaic's are approximately 40 percent efficient while commercial structures are averaging 20 percent efficiency. The energy efficiency also takes a hit when the DC direct current from the panels is converted to AC alternating current to be usable in buildings [2]. With growing research photovoltaics systems are becoming affordable and more efficient.

According to the U.S. Energy Information Administration, solar energy amounts to approximately 1 percent of the current total renewable energy consumption in the United States as seen in figure 1.1. This percentage is sufficiently less than other foreign countries such as Germany and Japan, which are currently the leading photovoltaic electricity providers/consumers. With the push for green energy all over the globe, the solar power industry has seen a 50 percent increase in panel manufacturing since 2007; bringing the total power to 3,800 MW, and doubling every two years [1].

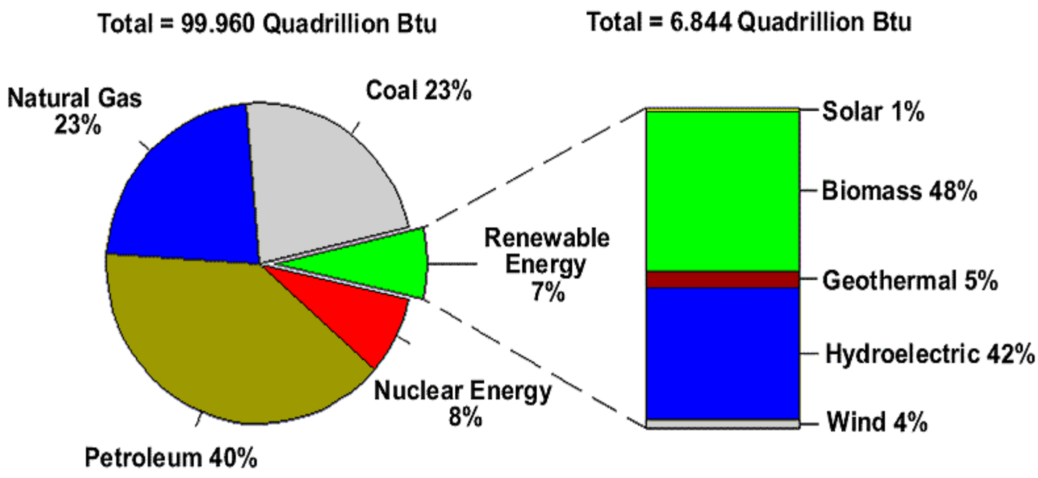

Figure 1.1 U.S. energy consumption by energy source, 2002-2006 [1].

1.3 Introduction to Scintillating Fibers

Scintillating fibers act as a wave guide, they are made with fiber core materials to produce photons in the visible range when high energy material pass through the core material [3]. They are a newer form of optical fibers and researchers are just beginning to understand how they can be used in engineering. Recently scientists have been able to use their properties in national security, medicine, and materials science.

Chapter 2

LIGHT

2.1 Properties of Light

Quantum mechanics describes light in two complimentary ways, either wave nature or particle nature called photons. In the 1900 Albert Einstein and Planck did research on this topic to try and describe the nature of light. They concluded that depending on the situation a photon may either be described as a particle or a wave, this concept is known as wave particle duality [4]. The speed of light in a vacuum is described as,

$$c = 3 \times 10^{8} \frac{m}{s}$$

A photon can be characterized by its wavelength or by its energy. They are both related through the following equation,

$$E = \frac{h\,c}{\lambda}$$

Where E is the energy, λ is the wavelength in micrometers, c is the speed of light in a vacuum and h is Planck's constant.

$$h = 4.135 \times 10^{-15} \frac{eV}{s}$$

Each incident color in the visible spectrum can then be described as different energies with different wavelengths. Due to the inverse relationship, higher energy photons have smaller wavelengths, while lower energy photons have longer wavelengths.

The photon flux gives the amount of energy striking an area in a given amount of time. This multiplied by the energy gives a power density of photon energy striking an area in an allotted amount of time.

$$\Phi = \frac{photons}{s\ m^2}$$

Power density,

$$H = \Phi \times \frac{hc}{\lambda} = q\Phi \frac{hc}{\lambda}$$

The power density can be modeled using blue and red light. Blue light has a shorter wavelength, and red light has a longer wavelength. Therefore, for the same intensity of light, the red must emit a larger number of photons than that of blue [5].

2.2 Radiation on Earth

Many different components affect the amount of solar radiation that reaches the earth's surface. Components such as absorption and scattering effects due to the atmosphere, pollution, location on the earth's surface, and the day and time.

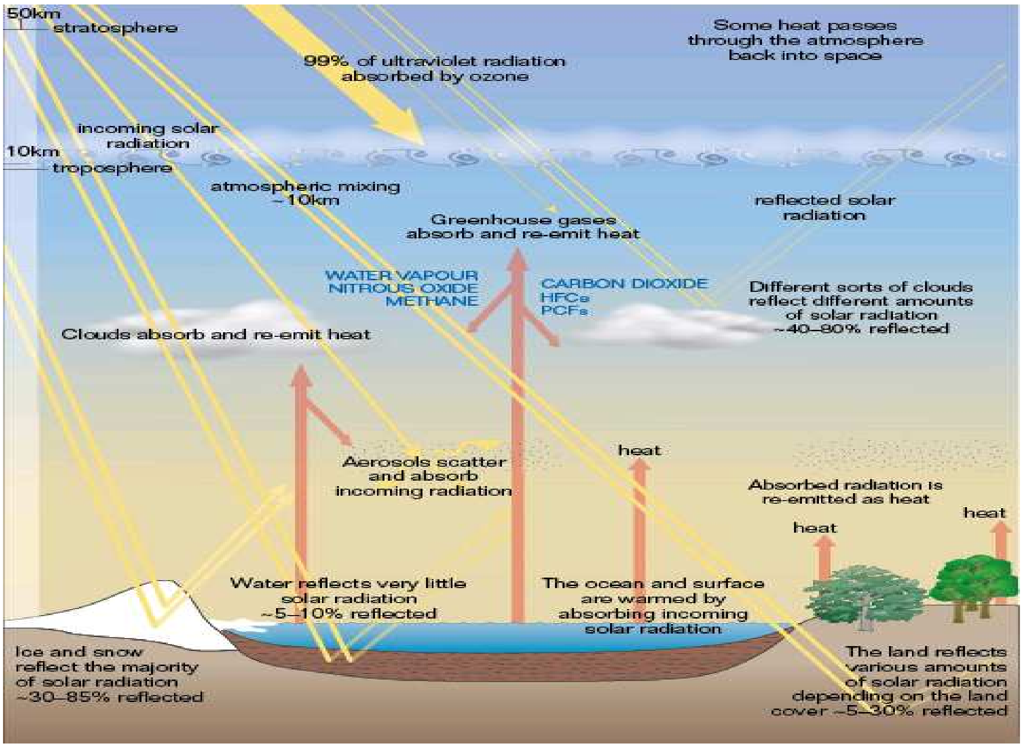

Figure 1.2 Depiction of solar irradiance and scattering/reflection loss mechanisms.

As the photons pass through the atmosphere the pollution and particles they interact with absorb their energy or deflect it, some of these effects are depicted in figure 1.2. When the sun is directly over head it has a shorter path length to the earth and therefore the photons experience less particle interference and the light seems to be more intense. When the sun is rising or setting the path length to the earth is longer and more photons experience a decrease in energy because it has a greater chance of being absorbed. That is why during morning and evening the sun appears redder and less intense and during midday it appears whiter and brighter.

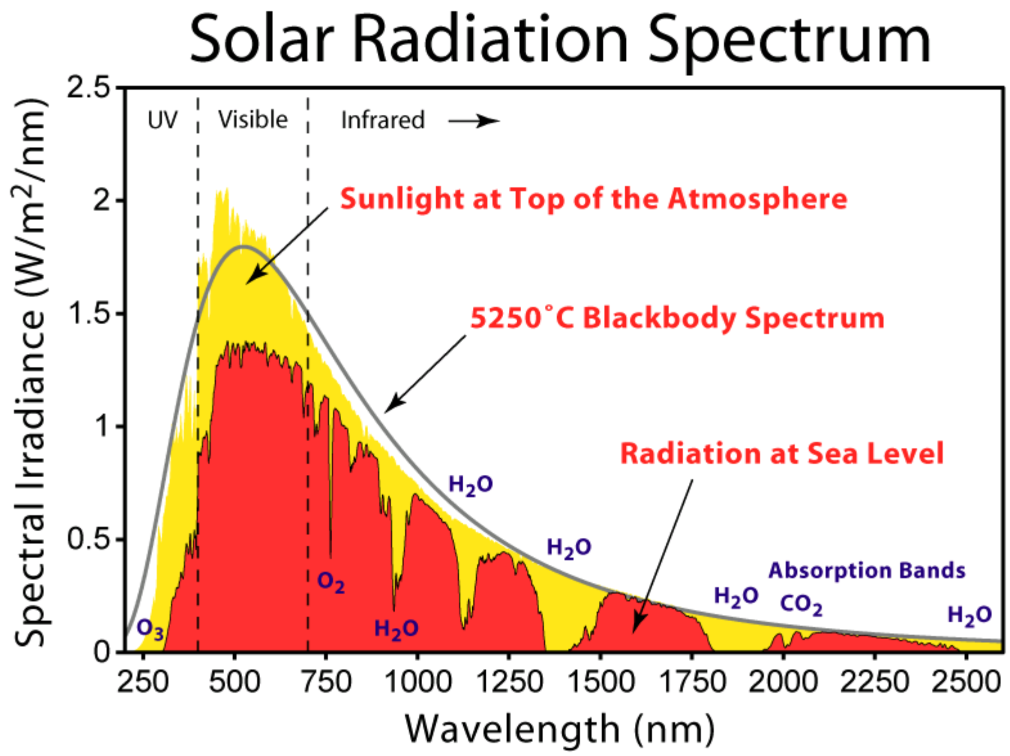

Figure 1.3 Solar radiation spectrum for direct light at top of Earth's atmosphere and at sea level [6].

Atmospheric scattering due to particles in the air is known to scientists as Raleigh Scattering. This is the elastic scatter of light or other electromagnetic radiation by particles much smaller than the wavelength of light which may be individual molecules. The Raleigh coefficient is,

$$\sigma_s = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$

From this equation we can see that Raleigh scattering is inversely proportional to the fourth power of the wavelength. This means that shorter wavelengths such as blue light will scatter more, and longer wavelength light such as red will scatter less. This effect is also known as diffuses sky radiation and explains why the sky appears to be blue [7].

2.3 Sun's Emission

The sun is considered an ideal blackbody emitter; it absorbs all incident electromagnetic radiation and then emits it as thermal radiation in a continuous spectrum depending on its temperature.

Plank's Radiation Law describes the spectral irradiance of a blackbody's electromagnetic radiation emitted at all wavelengths as a function of frequency and temperature.

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

ν = frequency

h = Boltzmann Constant

This equation can also be converted to a function of wavelength,

$$c = \lambda\nu$$

Therefore the spectral irradiance as a function of wavelength is,

$$I(\lambda) = \frac{2\pi hc^2}{\lambda^5\left(\left(e^{\frac{hc}{k\lambda T}}\right) - 1\right)}$$

H, c, and k are constants, T is the temperature in Kelvin, and lambda is the wavelength in micrometers[9].

One can determine the total power density emitted by the sun by observing the Stefan-Boltzmann Law and integrating over all the wavelengths which yields [8].

$$H = \sigma T^4$$

Using this, one can find the total power in energy per second that the sun is emitting.

$$P_S = 4\pi R_s{}^2 \sigma T_S^4$$

Where, R_s is the radius of the sun, T_s is the temperature of the sun, and

σ is the Stefan – Boltzman constant $= 5.67 \times 10^{-8} \frac{\mathrm{J}}{\mathrm{s\ m^2 K^4}}$

Therefore using the above equation the suns emitted power is,

$$P_S = 4\pi(6.96 \times 10^8 m)^2 \left(5.67 \times 10^{-8} \frac{J}{sm^2K^4}\right)(6000K)^4 = 4.13 \times 10^{26} \frac{J}{s}$$

The sun emits this energy in all directions so only a small fraction is absorbed by the earth. Also, only half of the earth sees this radiation at a time so the absorption area is equal to the area of a disk rather than that of a sphere, shown in figure 1.4.

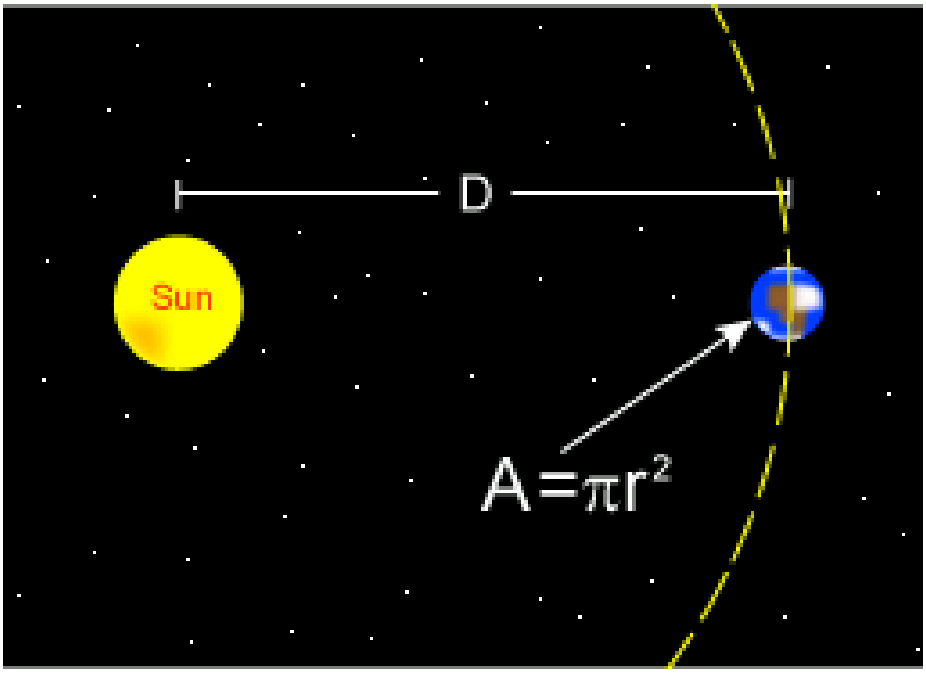

Figure 1.4 Sun and Earth solar energy relationship.

Taking this into account the power that the Earth then receives from the sun is,

$$P_{SE} = P_S\left(\frac{\pi R_E^2}{4\pi D^2}\right)$$

Where, D=1.5x10^8 km is the distance between the Sun and Earth.

$$P_{SE} = \left(4.13 \times 10^{26}\frac{J}{s}\right)\left(\frac{\pi(6.35 \times 10^3\,km)^2}{4\pi(1.5 \times 10^8\,km)^2}\right) = 1.85 \times 10^{17}\,\frac{J}{s}$$

The previously discussed factors of pollution and atmospheric interference also decreases the amount of energy absorbed therefore the actually power absorbed is,

$$P_{E\,ABS} = (1-\alpha)P_{SE}$$

Where, alpha is the albedo or reflectance of the Earth in the UV-V range [11].

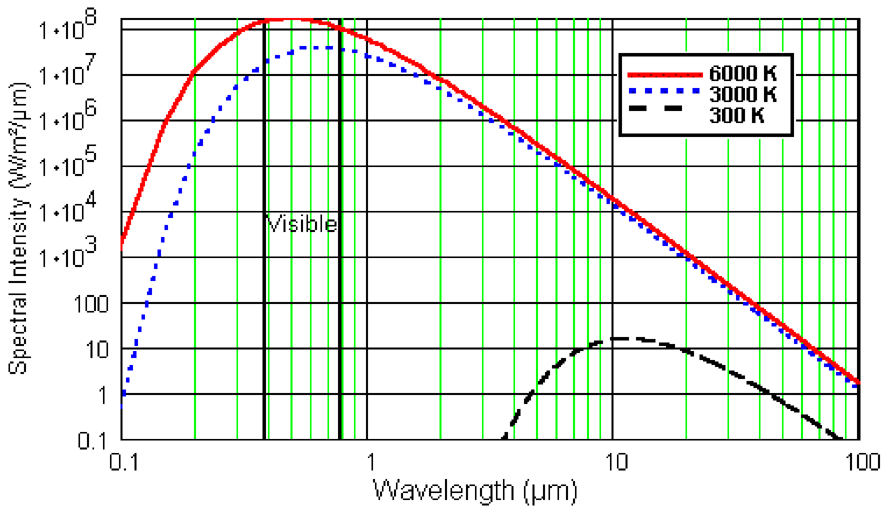

Figure 1.5 Log Graph of emitted black body irradiance as a function of temperature [8].

The intensity at earth's surface is greatly affected by cloud cover as seen in the graph below,

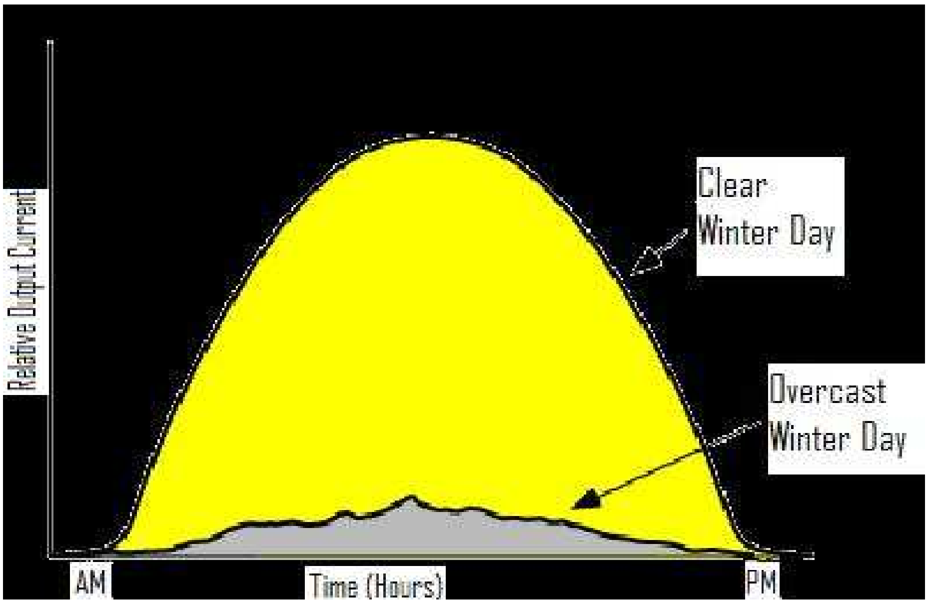

Figure 1.6 Solar panel current output on clear vs. cloudy day in Melbourne [9].

The solar insulation that is felt at the earth surface is dependent on the day of the year as well as the latitude in which the light is being measured. These two variables can be calculated to find the total sun hours experiences during the day, the peak insulation, and the total radiation accumulation over the entire day.

Chapter 3

SEMICONDUCTORS

3.1 Semiconductor Material

The basis of all photodiodes begins with a semiconductor material, most commonly crystalline solids like silicon or gallium arsenide. A semiconductor is a material with electrical conductivity, where the nature of the material allows electrons to flow freely above absolute zero. The atoms in a semiconductor are from group IV on the periodic table or are a mixture of group III and V, or group II and VI.

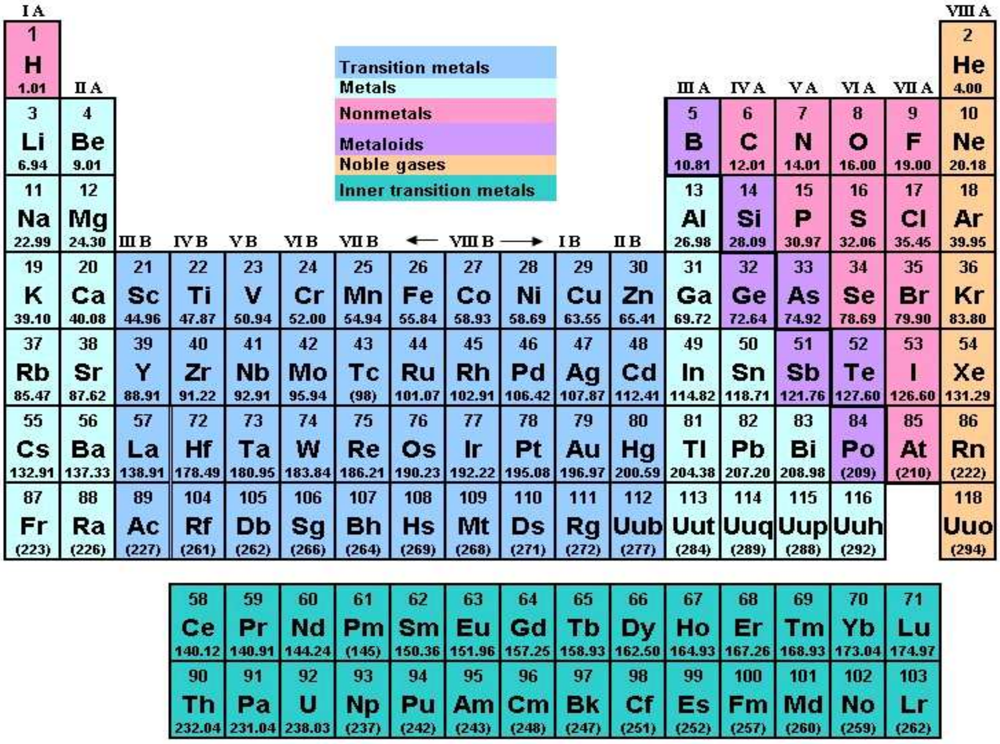

Figure 1.7 Periodic table of elements

3.2 Energy and Band Gap

The electrons in a semiconductor are held by covalent bonds. When the material is at room temperature the electrons have enough energy to break the ties of the covalent bonds and can participate in current flow and conduction. The presence of the bond allows for two distinct energy states that the electron can reside in. The electron cannot reside in between states it either has too low of energy and resides in its bound state in the valence band or it gains enough energy to break free of the bond and is moved into the conduction band. The minimum energy needed for the electron to become free is called the band gap. The band gap energy of silicon is 1.12 eV.

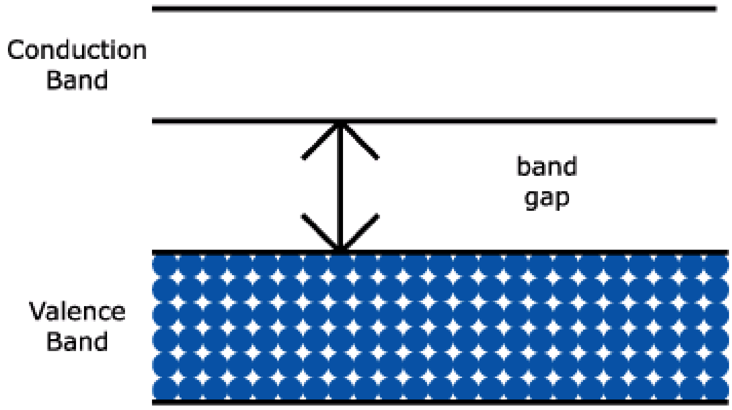

Figure 1.8 Band diagram depiction the full valence band, the band gap, and the empty conduction band [10].

When an electron gains enough energy to move to the conduction band it leaves an opening in the valence band. This opening allows for other electrons to then move into this open space again continuing the process of leaving behind an opening. This opening is known as a hole and is considered to be the movement of positively charged particle. These two particles, electrons and holes are thus known as charge carriers. The concentration of these carriers in the material is known as the intrinsic carrier concentration, denoted by n_i in material science. The intrinsic carrier concentration is dependent on the temperature of the material as well as the band gap. At higher temperatures the material has more thermal energy and therefore more electrons are excited and cross the energy gap into the conduction band, increasing n_i of the material. The following equation gives the intrinsic carrier concentration of silicon at temperature T,

$$n_i = 9.38 \times 10^{19} \left(\frac{T}{300}\right)^2 e^{\left(-\frac{6884}{T}\right)}$$

It is also possible to shift the balance of electron and holes by doping silicon, adding impurities to the material. Atoms with one more valence electrons then silicon are used to produce n-type semiconductors and atoms with one less valence electrons produce p-type semiconductor. In doped material there is always an excess of one type of carrier, known as the majority carrier, while the lower concentration is known as the minority carrier.

The law of mass action expresses the number of majority and minority carries as being constant and is expressed by,

$$n_i^2 = n_0 p_0$$

Where, n_0 and p_0 are the electron and hole equilibrium concentrations respectively. Using the law above the majority and minority concentrations for an n-type semiconductor is,

$$n_0 = N_D, p_0 = \frac{n_i^2}{N_D}$$

$$p_0 = N_A, n_0 = \frac{n_i^2}{N_A}$$

3.3 Absorption, Reflection, Transmission

Photons incident on the semiconductor will be absorbed, reflected, or transmitted. In materials science reflection and transmission is seen as a loss mechanisms. When the photon is absorbed the energy is transmitted to the electron to then raise it into the conduction band. The energy of the photon determines if it is absorbed or transmitted by the electron. The photon energy falls into three categories in comparison to the semiconductors band gap. If the photon energy E_{ph} is less than energy band gap E_g the interaction is weak and seems to pass right through the semiconductor. If the E_{ph} is more than energy band gap E_g, the photons are strongly absorbed. Lastly, if E_{ph} is equal to the band gap E_g, is efficiently absorbed and is the exact amount of energy to create an electron hole pair [11].

3.4 Absorption Coefficient

Due to the nature of semiconductors, they have a sharp edge in the absorption coefficients, because absorption is highly dependent on photon energy in comparison to the energy band gap. Any incoming light waves that consist of lower energy will not provide an adequate amount of energy to raise the electrons into the valence band because it is less than the band gap energy and consequently this light is lost. The absorption coefficient depends highly on wavelength of the light because wavelength determines photon energy. The following is the absorption coefficient equation with respect to wavelength and, k, the extinction coefficient.

$$\alpha = \frac{4\pi k}{\lambda}$$

3.5 Generation

The generation rate gives the number of electrons generated at each point in the device due to absorption of photons. The intensity at any point in the devices can be found using the following,

$$I = I_0 e^{-\alpha x}$$

And generation in the devices is,

$$G = \alpha N_0 e^{-\alpha x}$$

Where, N_0 is the photon flux at the surface, alpha is the absorption coefficient and x is the distance into the material.

3.6 Recombination

When an electron gains enough energy to move into the conduction band it is said to be in a meta stable state. It will eventually lose energy and fall back down into the valence band; this effect is called recombination [12].

The lifetime of a carrier is determined by the amount of time it is around before it recombines; this is related to the excess minority carrier concentration divided by the recombination rate.

$$\tau = \frac{\Delta n}{R}$$

This is the amount of time a carrier spends in its excited state prior to recombining. It is the time passed between generation and recombination.

Recombination is also highly dependent on the diffusion length. The diffusion length is the distance a carrier travels during its lifetime, prior to it recombining. Greater diffusion lengths indicate higher quality material in which the recombination rate is lower. The equation for diffusion length is,

$$L = \sqrt{D\tau}$$

Chapter 4

P-N JUNCTIONS

4.1 P-N Junctions

P-N junctions are formed when engineers bring together n and p type semiconductor materials. As explained previously, the n-type material has a high concentration of electrons and p-type has high concentration of holes. When the carrier diffuses across the junction they leave behind exposed ions at the donor impurity site of opposite charge. An electric field develops between the exposed positive and negative ions in the two materials; this area is called the depletion region.

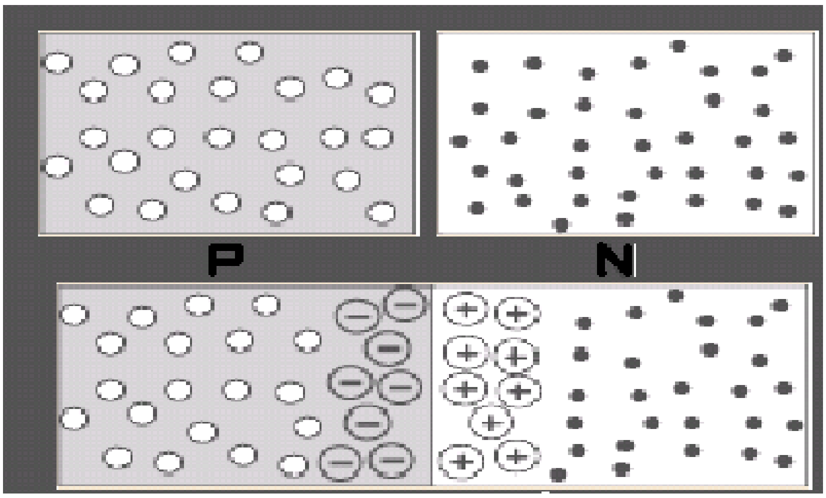

Figure 1.9 P-N junction depicting electron (dots) and holes (circles) as well as the charges created in the depletion region from the exposed ions [13].

The electric field in the depletion region quickly sweeps free carriers out of the area. Carriers that obtain high enough velocities will cross the junction and create diffusion current. The electric field causes a drift of carrier in the opposite direction. This process continues until the drift current and diffusion current is balanced, meaning they reach thermal equilibrium, which is then denoted by the Fermi energy.

4.2 Junction States

P-N junction diodes operate in three distinct states. Thermal equilibrium where there are no external inputs. The device as stated above has balanced diffusion and drift currents and so there is no net flow of current in the device. The second state is one in which an outside input such as voltage is applied however it does not change which time so it is known as steady state. Lastly, if an outside input is applied to the device and is changing rapidly with time the device is said to be in a transient state.

4.3 Forward Biased Diode

A forward bias corresponds to applying a positive voltage to the anode and a negative voltage to the cathode. In a p-n junction the anode is represented by the p-type substrate and the cathode is the n-type region. By applying this voltage it creates an electric field opposite to the intrinsic field within the depletion region. Because the built in electric field is usually higher than the applied field, thus the net electric field in the depletion region is reduced. Reducing the electric field therefore reduces the barrier the carrier's sense and the diffusion current increases while the drift current remains essentially the same. This is the basic idea used to create solar cells. The diodes in solar panels are forward biased to allow for greater current flow due to the reduced barrier.

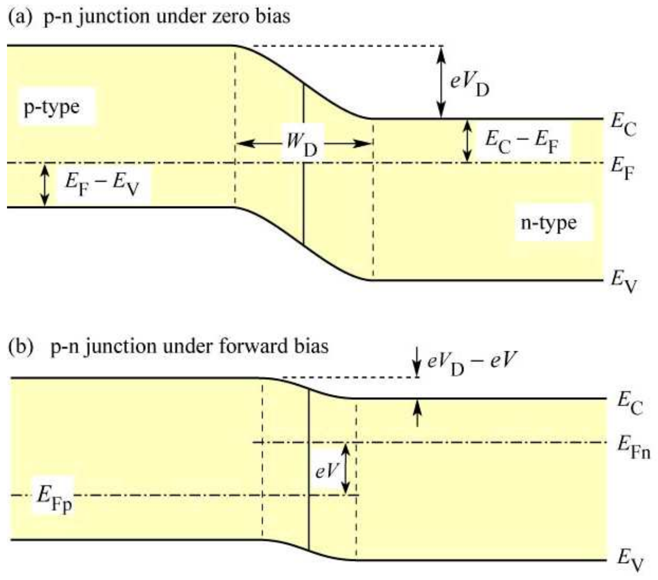

Figure 1.10 Band diagram of P-N junction with zero bias and forward bias. The forward bias also depicts the split Fermi energies [14].

The Shockley Ideal Diode Law, named after William Shockley states,

$$I = I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

Where,

I= Net current flow through diode
I_0= dark saturation current, leakage current
V= applied voltage
q= electron charge -1.602x10^{19} C
k= Boltzmann constant 1.38x10^{-23} J/K
T= temperature in K

Non Ideal Diode Equation

$$I = I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$

Where n is an ideality factor between 1 and 2.

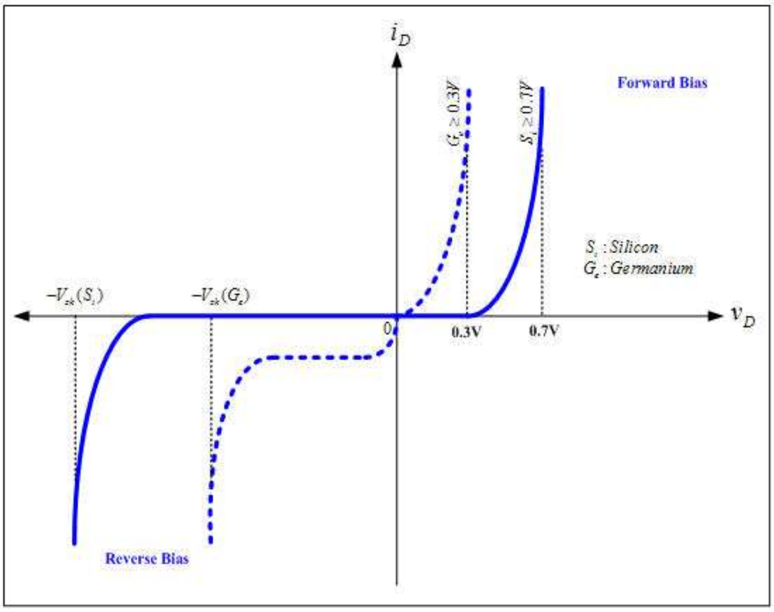

Figure 1.11 I-V curves for Silicon and Germanium.

The major differentiating factor of any diode is the dark current, I_0. This is a measure of the recombination in the device. The greater the recombination, the larger the dark current, I_0 is also highly dependent on the quality of the substrate material as well as temperature.

4.4 Solar Cell

Solar cell make use of the physics within a p-n junction to use light generated current as the external input to create the electron hole pairs, and current flow. The electrons within the p-n junction receive energy from photons; this is known as light generated current. The photon energy must be greater than the band gap, to move the electron from the valence band into the conduction band as stated previously.

The collection probability of a solar cell determines the efficiency of the cell. The collection probability is determined by the number of light generated carriers that make it to the depletion region, that are then swept across the junction. The higher the number of swept light generated carrier, the greater the collection probability. Many factors affect that collection probability, such as the diffusion length of the carriers, recombination, and the region in which the carrier is generated. If the carrier is generated more than one diffusion length away from the depletion edge collection probability decreases. The higher the quality of solar cell materials used, the greater the diffusion length, which implies greater collection probability.

4.5 Quantum Efficiency

The quantum efficiency is the greatest measure to determine the overall efficiency of a solar cell. The quantum efficiency is a ratio or collected carriers versus incident photons. It would be ideal for every photon incident on the cell to then produce one carrier that is then collected by the solar cell; however this is impractical in reality [15].

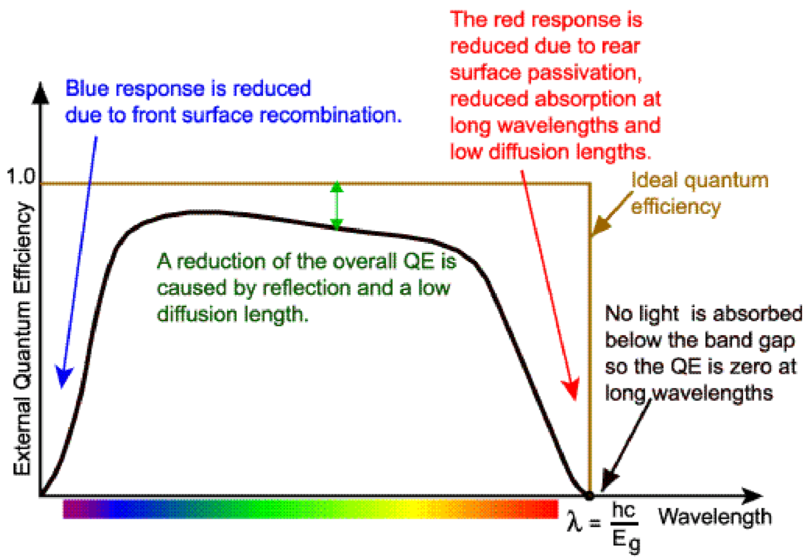

Figure 1.12 Quantum efficiency of an ideal solar cell in comparison to wavelength [15].

4.6 Cell Efficiency

There are many different factors that determine how efficient a solar cell or photo detector is. The quality of material determines the band gap, as well as the carrier concentrations, and diffusion lengths. Anti-reflective coatings and texturing also increases the efficiency. Anti-reflective coatings and texturing utilize destructive interference so that all the incoming light waves are absorbed and not reflected from the surface of the cell.

Passivation is also another mechanism that industry uses to increase cell efficiency. When the semiconductor materials are cut, dangling bonds reside on the surface. If left alone these bonds will latch on to generated carriers and take away from the generated current. Passivation using hydrogen allows scientist to essentially tie up the loose bonds and eliminate generated current loss.

The short circuit current is the current flowing through the cell when the voltage is zero and the open circuit voltage is the maximum voltage across the cell when the current is zero [16]. These two factors, along with the maximum power determine the performance of the cell called the fill factor. The fill factor is the ratio of the maximum obtainable power to the actual obtainable power

$$P_{max} = I_m V_m$$

$$FF = \frac{P_{max}}{V_{oc} I_{sc}}$$

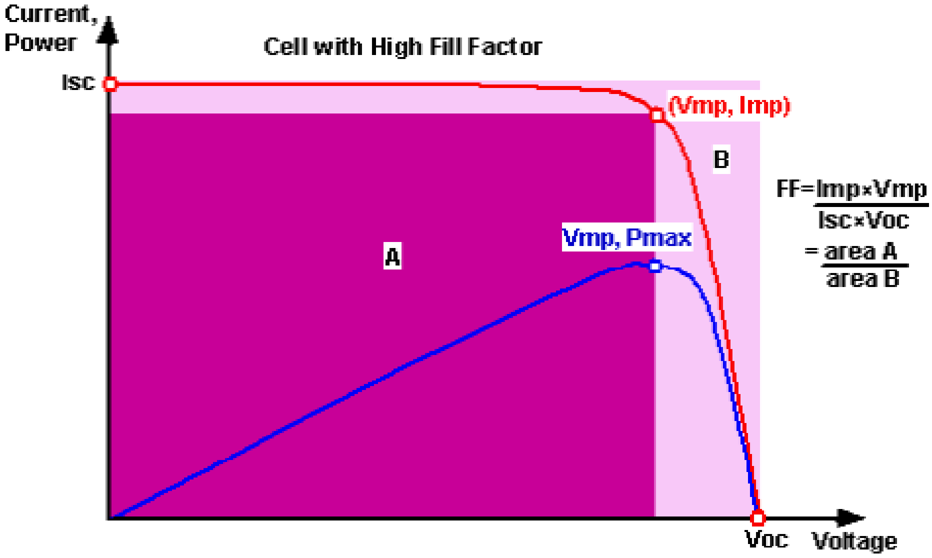

Figure 1.13 Graph showing fill factor of solar cell [16].

The fill factor for typical solar cells is FF>0.7, while lower grade cells have a fill factor of 0.4<FF<0.7.

Chapter 5

WAVE GUIDES

5.1 Wave Guiding

A waveguide is a structure that traps and guides all different types of waves such as sound, electromagnetic, and light. For every type of wave there is a different structure, geometry, or material that is utilized to optimally direct the energy of the wave in the desired direction. Waves in open space propagate in all directions, for example sound waves or light waves. Thus they lose their power proportionally to the radius, or square of the distance. The benefit of the waveguide allows scientist to confine the wave so that it only propagates in one desired direction and ideally maintains its full power. This is done by total reflection from the waveguide walls and the pattern of movement can be described as a zigzag motion, depicted in figure 1.12 below.

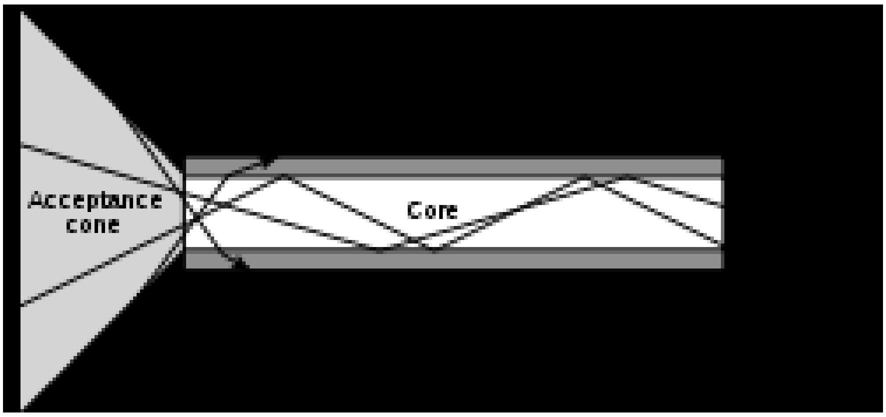

Figure 1.14 Depiction of the zig-zag motion in a waveguide.

5.2 Optical Fibers

For the application of this paper, we focus on optical fibers. These are thin, flexible, transparent fibers that also perform wave guiding by transmitting light from one end to the other. In today's society more things are transforming from old metal wire based application to fiber optics. The benefits of optical fibers is that they can transport signals longer distances with less loss and are immune to electromagnetic interference. The fibers consist of a solid core surrounded by a transparent cladding with a lower refraction index. The light is kept within the core by utilizing the concept of total internal reflection, thus allowing it to act as a waveguide. The refraction index of light in a vacuum is 1, the typical refraction index in the cladding is 1.52 and the core is 1.62. The index of refraction is determined by dividing the speed of light in a vacuum by the speed of light in another medium.

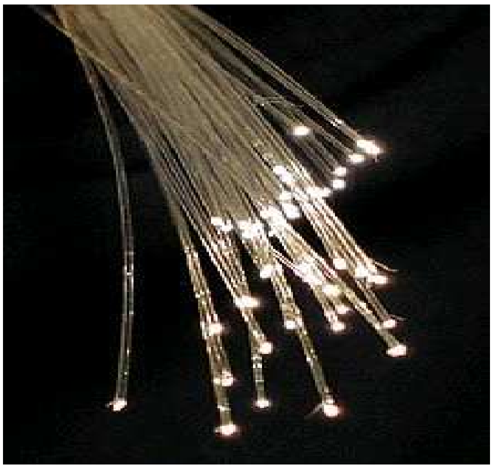

Figure 1.15 Bundle of optical fibers.

5.3 Total Internal Reflection

Total internal reflection occurs when light traveling in a medium encounters a second medium with a smaller index of refraction. This causes the ray to be bent away from the normal so that the exit angle is greater than the incident angle. This exit angle will eventually reach a critical angle of 90 degrees and for incident angles that are greater than the critical angle, total internal reflection will occur. This critical angle can be calculated using Snell's Law and setting the refraction angle to 90 degrees,

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

Where, n_1 is the refractive index of the cladding and n_2 is the refractive index of the core.

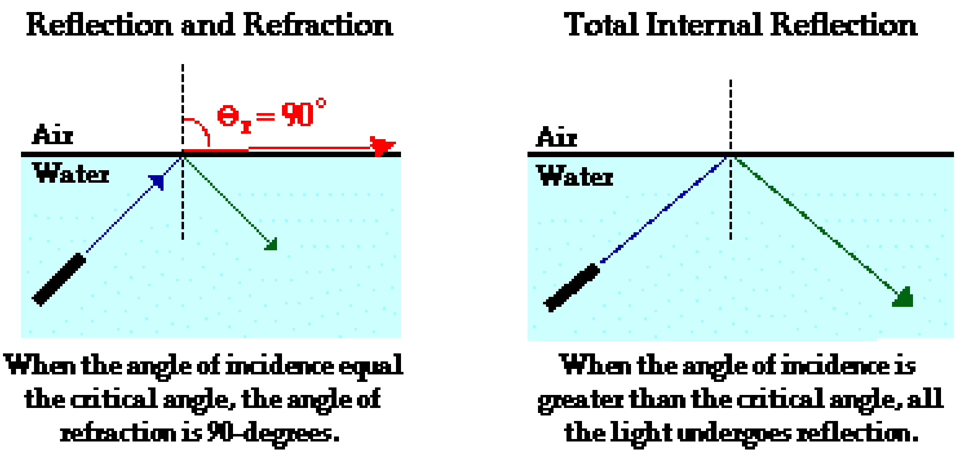

Figure 1.16 Reflection and refraction for angle < 90, and incidence angle > 90.

5.4 Manufacturing Scintillating Fibers

Scintillating fibers are one form of fiber optics that utilize the principles and concepts of fiber optic wave guiding to transport light from one end of the fiber to the other. There are two different processes in which Nanoptics Inc. produces the fibers used for the experimentation in this paper. The fibers are made from the monomer Polystyrene or the polymer PVC (Polyvinyl Chloride). The first process uses a stretching machine that heats the liquid monomer pellets with concentrated dyes. The mixture is heated into rod form. It then goes into a stretching tower where the heated rod is pushed down and at the bottom the fiber is pulled. The drawing power of the rod can be gauged to determine the radius of the output fibers. When the rod is pushed faster, or the pull is slower the fibers will be thicker.

The second process uses a melting extruder where the previously dyed polymer pellets are melted and then forced into hollow rods that are then extruded from the machine. The base polymer PVC is in the low ultra violet range and therefore a primary dye is added to absorb the UV light and emit at higher frequencies. A secondary dye is added that absorbs the emissions and again readmits at a higher frequency. This helps the fiber maintain its cross sectional shape. The extruder process is faster and more efficient; however the residence time of the polymer is around ten minutes. Therefore it must be accurately timed to produce high quality fibers.

Although both monomer and polymers are used, PVC is better suited for optical fiber application because its scintillating efficiency is higher, however it is more expensive.

Chapter 6

SCINTILLATING FIBER TEST

6.1 Test Set-Up

A Silicon photo detector used for testing was manufactured by ThorLabs part number DET36A. It detects wavelengths within the 350-1100 nanometer range with a peak wavelength of 970 nm. The diode is forward biased at 10 V and has an active detection area of $13mm^2$. The dark current I_0 is 0.35 nA.

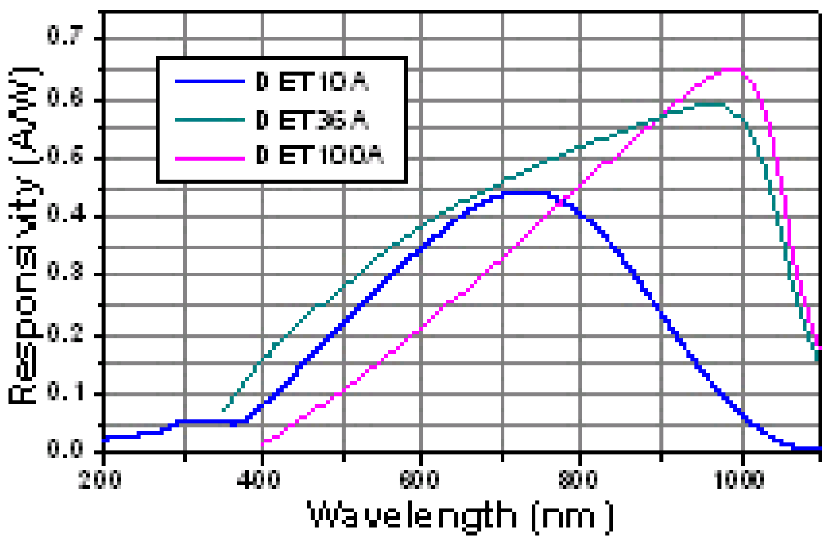

Figure 1.17 Response of photo detector versus wavelength, we are interested in DET36A provided by ThoreLabs.

Figure 1.18 Photo detector with ¼” shield to block outside light

The scintillating fibers that were tested were manufactured by Nanoptics Inc. An assortment was assessed with a radius ranging from 0.035” to 0.118” and colors were yellow, red, and orange. It would be ideal to test every color at each radius; however some of the fibers are not produced at all radius levels.

Table 1.1 Table of tested colors vs. radius

Color	Radius 1	Radius 2	Radius 3	Radius 4
Yellow		0.04"	0.078"	
Orange	0.035"		0.078"	0.118"
True Red	0.035"	0.04"	0.078"	0.118"

Lastly, a universal multi-meter was used to measure the current (uA) output of the photo detector.

Figure 1.19 Universal multi-meters.

An overall set up is pictured below. The testing was done on clear days between the hours of 11 am and 1 pm when the sun is overhead and the irradiance is greatest.

Figure 1.20 Overall setup, photo detector, fiber, and multi-meter.

6.2 Assumptions

As previously stated the testing was performed on clear sunny days only between the hours of 11am and 1pm such that there was little flux in the irradiance from the sun. A quarter inch black shield was used to block out any outside light, such that the light generated current was only being produced by the scintillating fibers. We want to figure out the photon energy produced by each color, yellow with wavelength of approximately 570 nm, orange with wavelength about 590 nm, and red light with wavelength approximately 650 nm. Using a previous equation that relates wavelength to energy, we can calculate the photon energy of the light.

The energy of yellow light,

$$E_{Yellow} = \frac{h\,c}{\lambda} = \frac{\frac{(6.626 \times 10^{-34} Js)\left(2.98 \times 10^{8} \frac{m}{s}\right)}{570 \times 10^{-9} m}}{1.602 \times 10^{-19} \frac{J}{eV}} = 2.162\ eV$$

The energy of orange light,

$$E_{Orange} = \frac{h\,c}{\lambda} = \frac{\frac{(6.626 \times 10^{-34} Js)\left(2.98 \times 10^{8} \frac{m}{s}\right)}{590 \times 10^{-9} m}}{1.602 \times 10^{-19} \frac{J}{eV}} = 2.089\ eV$$

The energy of red light,

$$E_{Red} = \frac{h\,c}{\lambda} = \frac{\frac{(6.626 \times 10^{-34} Js)\left(2.98 \times 10^{8} \frac{m}{s}\right)}{650 \times 10^{-9} m}}{1.602 \times 10^{-19} \frac{J}{eV}} = 1.896\ eV$$

The band gap energy for silicon is 1.12 eV, therefore it is assumed that yellow light will be better absorbed and have greater light generated current, followed by orange, and red respectively.

As the radiuses of the fibers are increased there is a larger surface area which allows for more photon flow emission. The emitting surface area can be calculated using basic geometry,

$$A = \pi r^2$$

Lastly, it is assumed that longer fiber lengths will allow for more light generated photons to be formed in the scintillating fiber waveguide, prior to reaching the end where testing occurs.

6.3 Testing 0.035” Fiber Radius

Note each fiber was tested using a five trial method to account for small fluctuations in the current output. The trials were then averaged overall to produce a final output.

The first sets of fibers were orange and red with a radius of 0.035 inch. These fibers were measured in meter increments that ranged from 1.016 m to 0.0254 m.

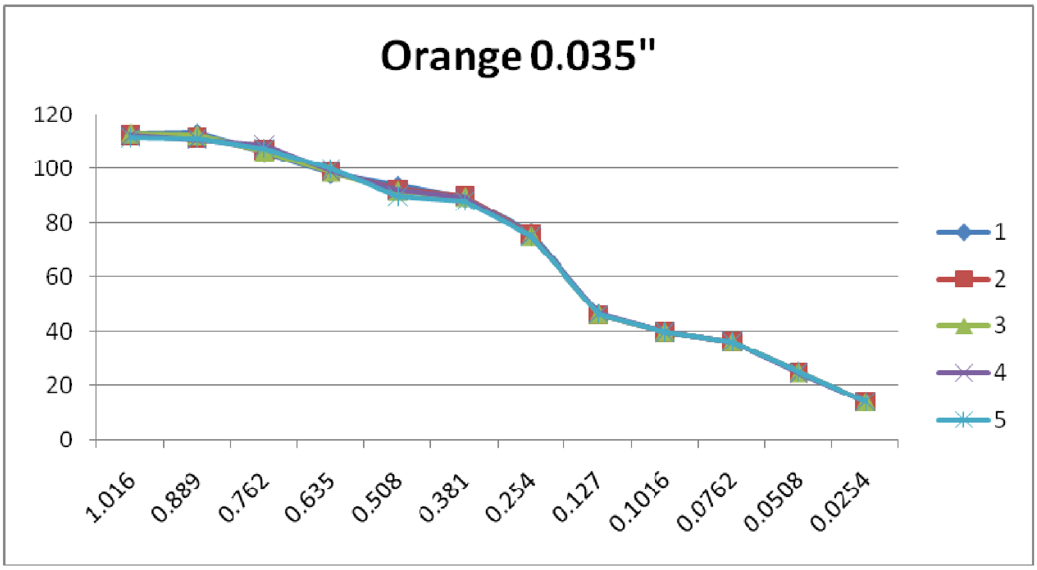

Figure 1.21 Orange fiber 0.035” radius current outputs vs. fiber length.

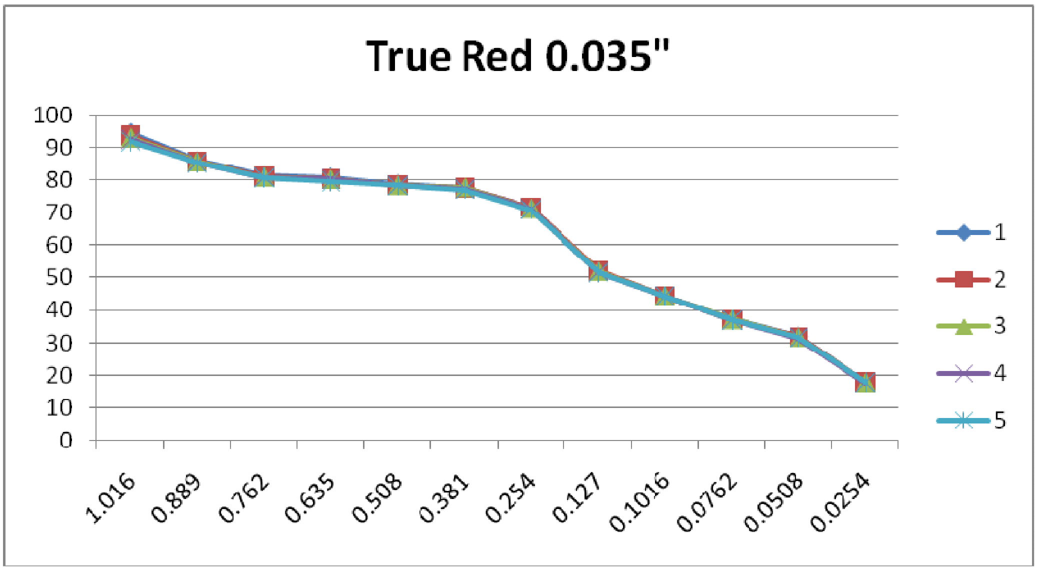

Figure 1.22 True red fiber 0.035” radius current output vs. fiber length

6.4 Testing 0.040" Fiber Radius

The 0.04" radius fibers were manufactured at much larger lengths. The manufacturer was able to produce 40 meters of fibers to determine if length greatly affected the light generated current produced by the fibers. These fibers were provided in yellow and true red. These fibers were tested in increments that ranged from 40 meters to 0.0254 meters.

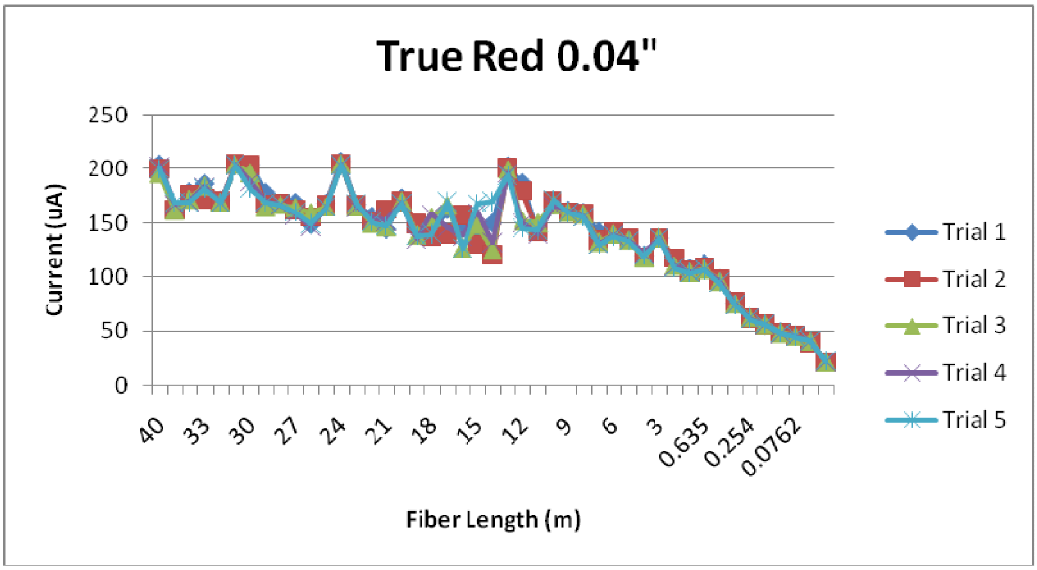

Figure 1.23 True red fiber 0.040" radius current output vs. fiber length

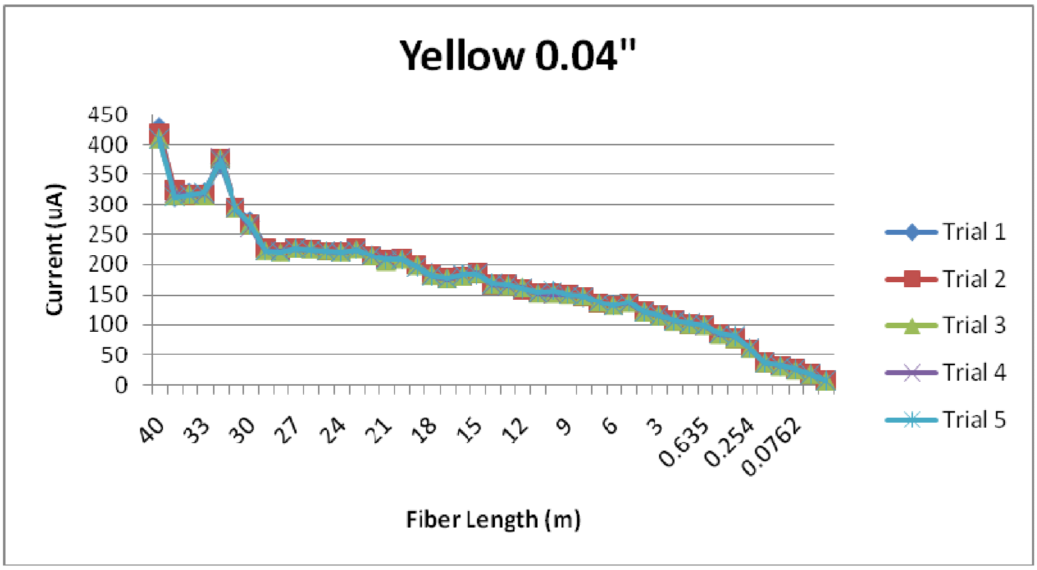

Figure 1.24 Yellow fiber 0.040" radius current output vs. fiber length

6.5 Testing 0.078" Fiber Radius

I was provided all three colors of fibers to measure with 0.078" radius. This allows seeing the entire spectrum from yellow to red and how the color and length affects the absorption. These fibers were also tested in increments from 1.016 meters to 0.0254 meters.

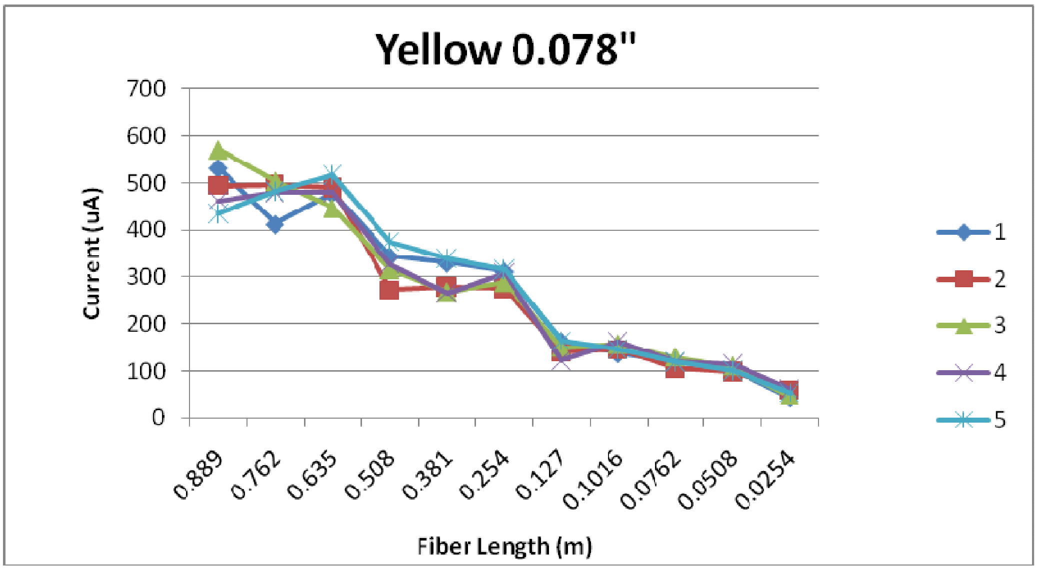

Figure 1.25 Yellow fiber 0.078" radius current output vs. fiber length

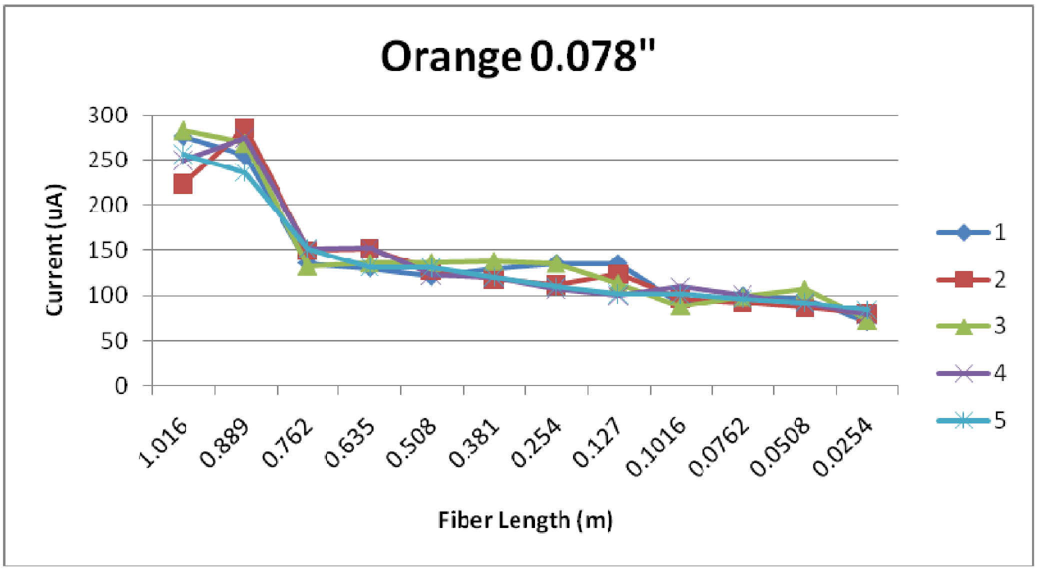

Figure 1.26 Orange fiber 0.078" radius current output vs. fiber length

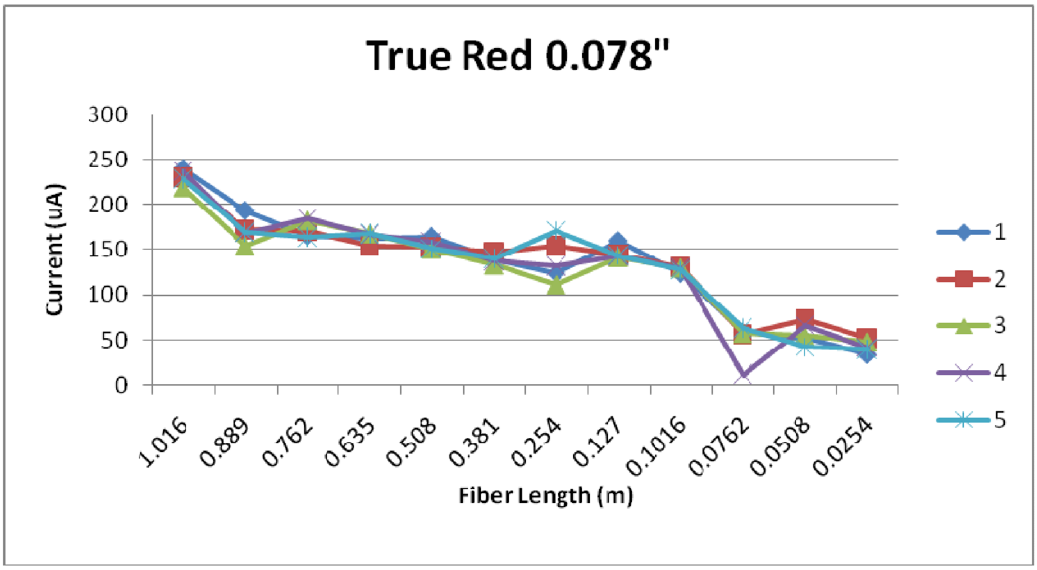

Figure 1.27 True red fiber 0.078" radius current output vs. fiber length

6.6 Testing 0.118" Fiber Radius

This was the largest radius of fiber tested. The manufacturer was able to provide red and orange fibers with this larger radius. These fibers were also tested at lengths between 0.0254 meters up to 1.018 meters.

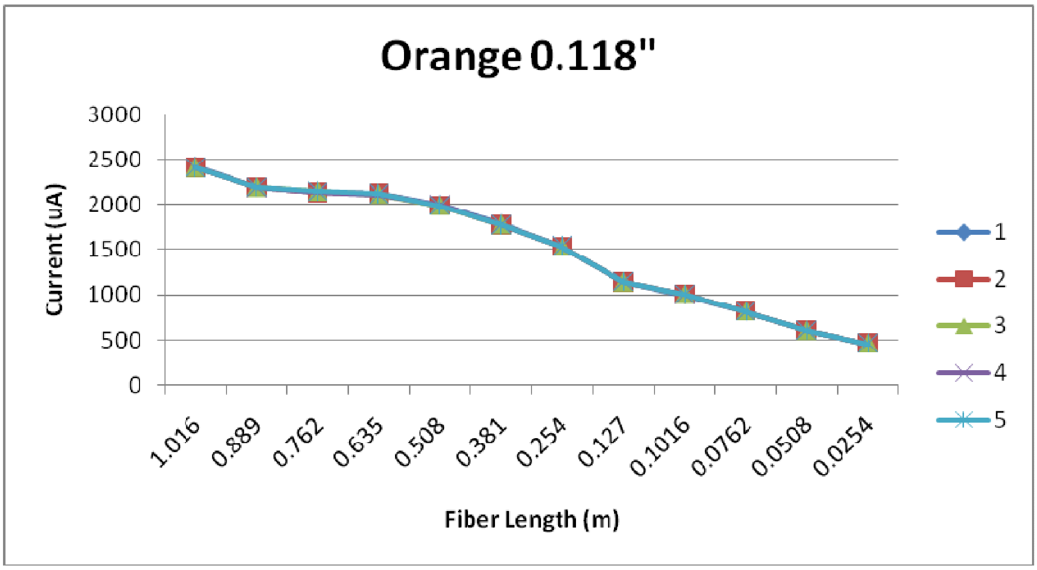

Figure 1.28 Orange fiber 0.118” radius current output vs. fiber length

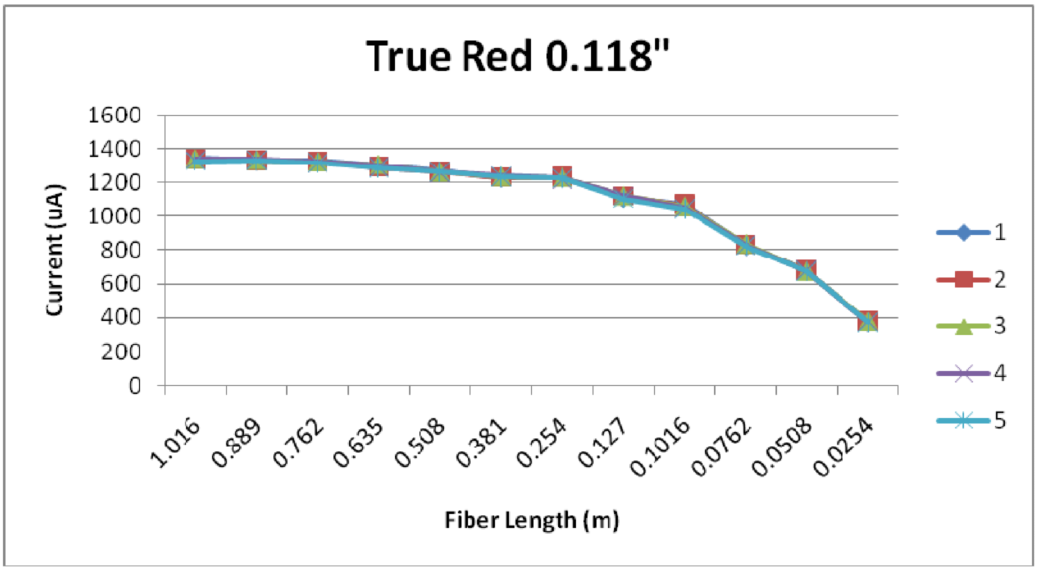

Figure 1.29 Orange fiber 0.118” radius current output vs. fiber length

6.7 Conclusion

The previous assumptions were that larger radius as well as longer lengths will produce higher light generated currents within the silicon photo detector. Photon energies for each color were calculated using their corresponding wavelengths and yellow light with higher photon energy will have larger currents. To determine this each of the above graphs were averaged and then plotted against each other.

It was easiest to observe the effects of wavelength and color first.

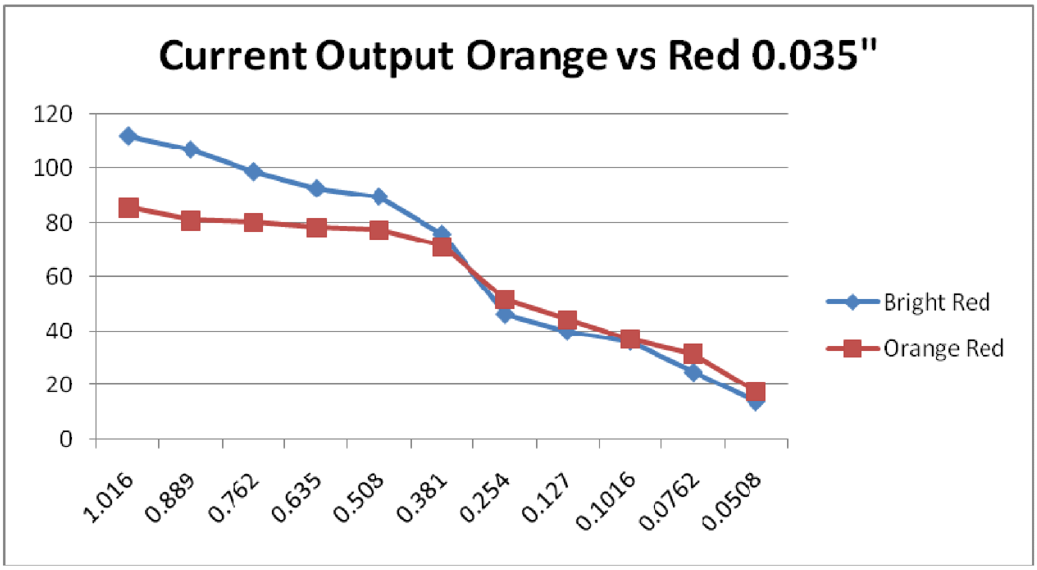

Figure 1.30 Current outputs for orange and red fibers 0.035" radius.

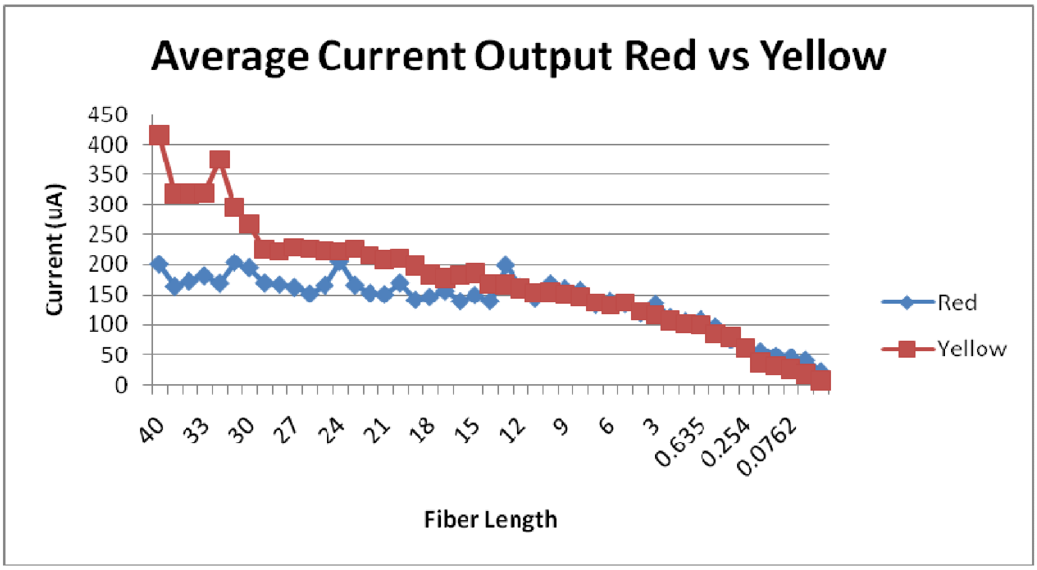

Figure 1.31 Current output for red and yellow fiber radius 0.040”

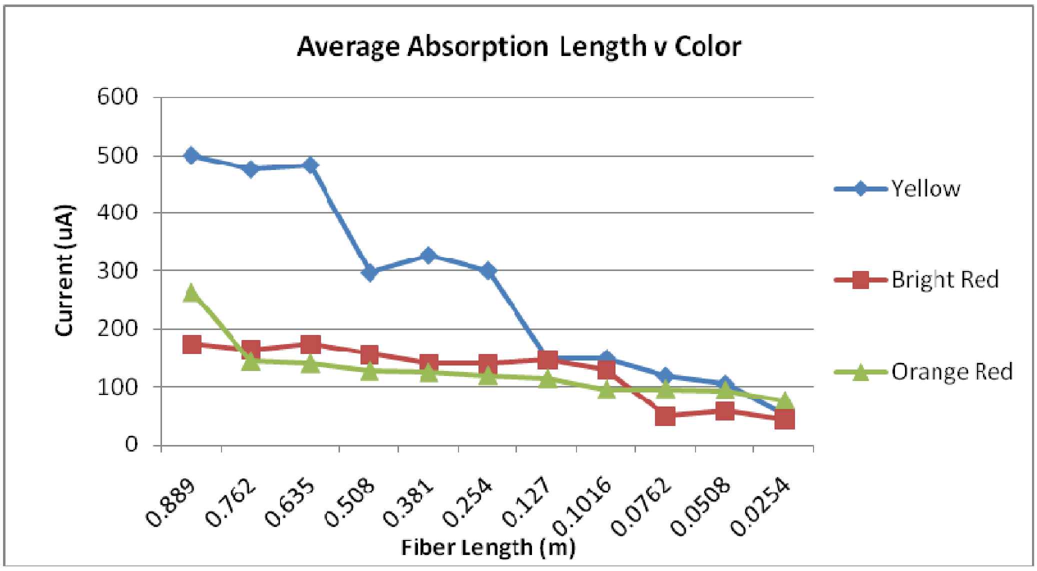

Figure 1.32 Current output for all colors, fiber radius 0.078”

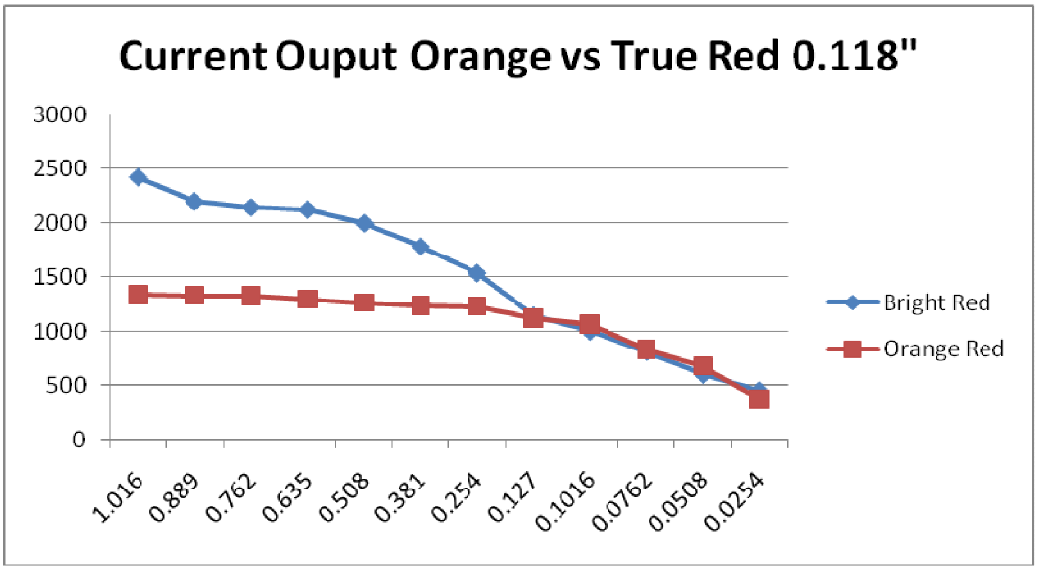

Figure 1.33 Current output of orange and red fiber radius 0.118"

From the figures 1.27 and 1.28 it is concluded that in each instance where yellow fibers were measured, they had significantly larger light generated currents compared to that of red and orange. Figures 1.26, 1.27, and 1.28 also verify that orange fibers also produce greater currents within the photo detector which was expected. It was also necessary to compare the different sized radius of each fiber against each other to grasp if radius majorly affected the produced current.

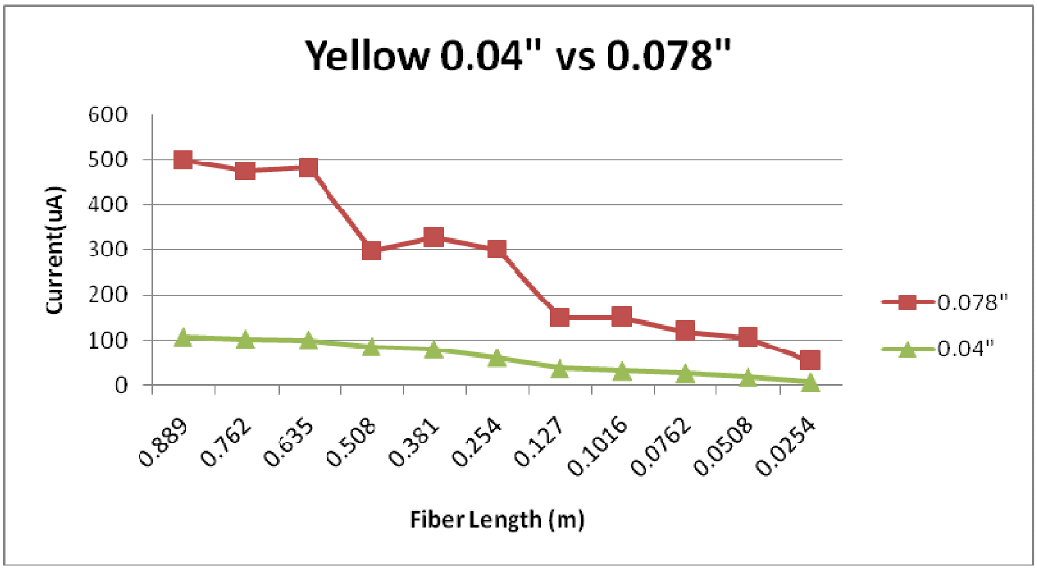

Figure 1.34 Yellow fiber current output 0.04" radius vs. 0.078"

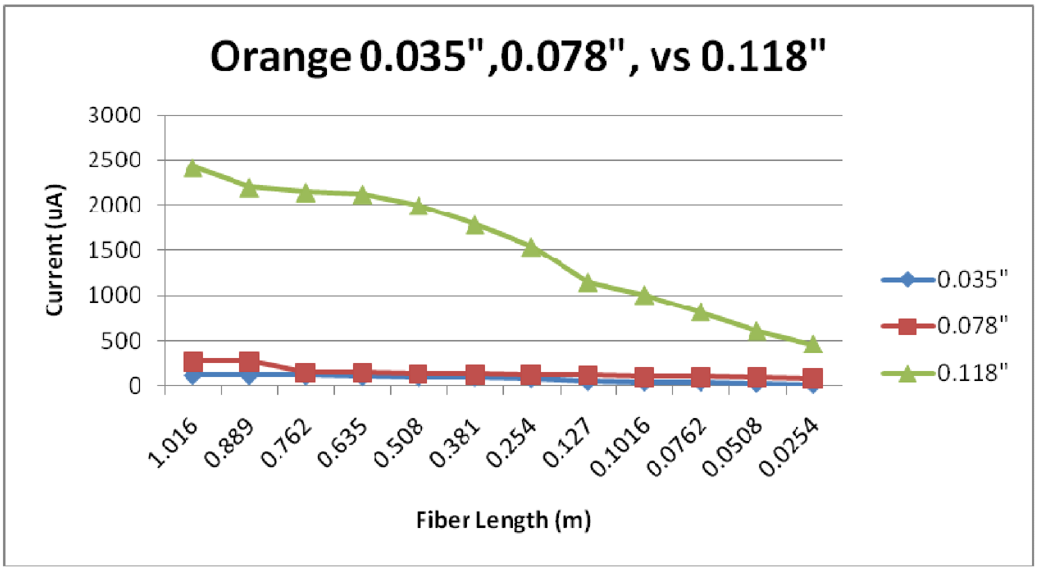

Figure 1.35 Orange fiber current output 0.04" radius vs. 0.078" and 0.118"

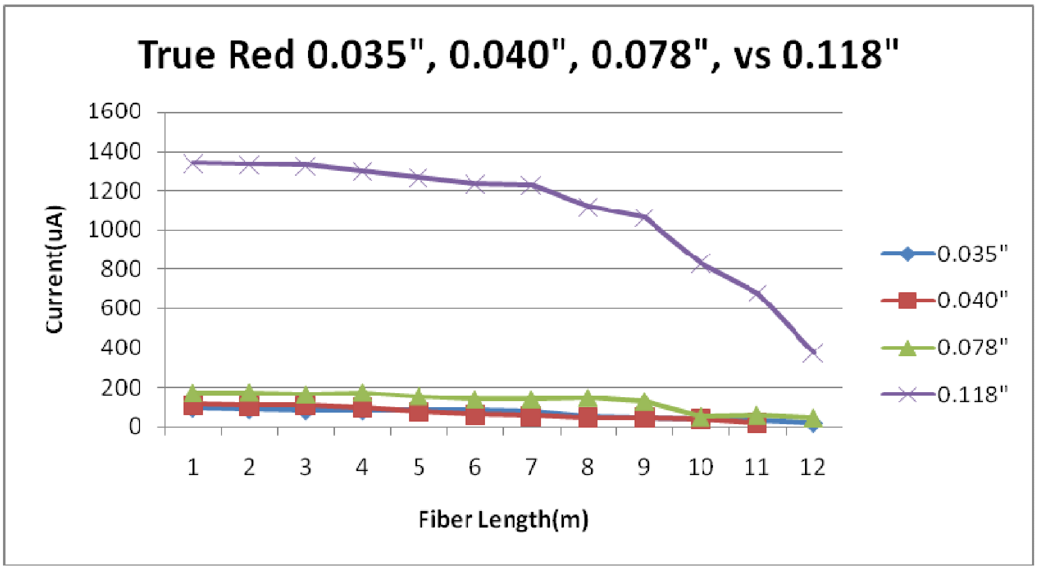

Figure 1.36 True red fiber current output 0.035” radius vs. 0.040”, 0.078” and 0.118”

From the three plots above it is obvious that radius has a large impact on the light generated current in the photo detector. Comparing the orange and red fibers it is noted that the current ratio between the largest radius fiber at 0.118” and the smallest radius 0.035” are both approximately 2.1 and the ratio for those colors for radius 0.118” compared to 0.035” is approximately 10 for both.

APPENDIX A

FIBER TEST TRIALS

Table 1.2 0.035” Orange fiber testing

Orange 0.035"						
Length(m)	Trial 1	Trial 2	Trial 3	Trial 4	Trail 5	AVG all Trials
1.016	112.9	112.6	113	112.7	111.8	112.8
0.889	113.2	111.6	112.4	111	111.5	112.05
0.762	105.8	107	106.4	108.8	107.7	107
0.635	98.1	99	98.8	99.4	100.3	98.825
0.508	93.9	92.6	92	92.3	90	92.7
0.381	89.2	90	89.7	89.8	88.2	89.675
0.254	76.5	76	75.3	75.6	75.4	75.85
0.127	46.4	46.2	46.3	46.6	46.5	46.375
0.1016	40	39.9	39.9	39.9	39.8	39.925
0.0762	36.4	36.3	36.2	36.3	36.1	36.3
0.0508	25.1	25	24.9	24.8	24.9	24.95
0.0254	14.3	14.1	14	14.1	14	14.125

Table 1.3 0.035” True Red fiber testing

True Red 0.035						
Length(m)	Trial 1	Trial 2	Trial 3	Trial 4	Trail 5	AVG all Trials
1.016	94.5	93.9	93	92.5	91.8	93.14
0.889	85.9	85.8	85.6	85.4	85.3	85.6
0.762	81.3	81.1	80.9	80.8	80.7	80.96
0.635	80.8	80.3	80.3	80.2	79.5	80.22
0.508	78.8	78.6	78.4	78.2	78.2	78.44
0.381	77.6	77.8	77.8	77.2	77	77.48
0.254	71.4	71.8	71.3	71	70.8	71.26
0.127	52	52.2	52	51.8	51.6	51.92

Table 1.3 Cont.

0.1016	44.5	44.4	44.4	44.3	44.2	44.36
0.0762	37.3	37.2	37.2	37	37.1	37.16
0.0508	32.1	31.9	31.7	31.6	31.5	31.76
0.0254	17.9	17.8	17.8	17.7	17.8	17.8

Table 1.4 0.040" Yellow fiber testing

Yellow 0.04"						
Length (m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	AVG all Trials
40	428.3	419	410.5	410.9	410.3	415.8
35	312.4	325.8	317.3	319.8	313.2	317.7
34	320.4	316.8	317.9	318	317.5	318.12
33	320.9	317.8	316.4	318.8	320.5	318.88
32	367	377.3	378	378.8	374.7	375.16
31	295.9	296	294.2	294	294.6	294.94
30	272.2	267.1	267.5	262.8	266.9	267.3
29	228.6	227.9	223.8	223.6	223.9	225.56
28	221.4	222.6	222	223.7	220.9	222.12
27	228.2	227.9	227.3	227.8	227.9	227.82
26	226.6	226.6	226.1	226.5	226.3	226.42
25	222.7	222.6	224	224.1	223.3	223.34
24	224	222.8	222	220.9	221.8	222.3
23	226	227.1	226.2	226.3	224.5	226.02
22	216.7	215.9	215	214.9	215.8	215.66
21	207.4	209.3	205.8	211.7	207.9	208.42
20	211.3	210.7	209.8	209.5	209	210.06
19	197.8	199.3	199.5	195.8	195.5	197.58
18	186	184.3	183.4	182.9	181.5	183.62
17	177.8	178.7	177.9	176.5	176.9	177.56
16	183	181.1	181.9	183.5	183.4	182.58
15	185.4	185.8	186.4	185.7	183.9	185.44
14	168.4	167.2	168.3	168.1	169.9	168.38

Table 1.4 Cont.

13	168	167.8	166.3	165	166.8	166.78
12	159.7	159.2	163.4	162.8	160.7	161.16
11	153.2	152.8	152.4	152.6	153.8	152.96
10	156.6	153.4	151.6	150.9	157.8	154.06
9	150.3	150.6	150.2	150.6	150.1	150.36
8	144.7	146.6	147.8	148	147.6	146.94
7	137.1	136.9	137.4	137.9	137.2	137.3
6	135	133.4	133.1	132.8	131.9	133.24
5	137.2	137.8	137.4	136.6	137.5	137.3
4	124.2	123.7	122	121.7	120.8	122.48
3	116.5	116.9	116.3	116.2	116	116.38
0.889	108	107.9	106.9	107	106.5	107.26
0.762	101.6	101	101.6	102.8	103.2	102.04
0.635	100	100	99.9	99.6	99.7	99.84
0.508	85.5	85.6	85.4	85.3	85.4	85.44
0.381	77.3	78.4	78.5	81.7	82	79.58
0.254	61.6	61	61.2	61.3	61	61.22
0.127	37.3	37.3	37.1	37	36.7	37.08
0.1016	31.3	31.5	31.5	31.6	31.7	31.52
0.0762	26	25.9	26.1	26.1	26.2	26.06
0.0508	18.6	18.5	18.6	18.5	18.6	18.56
0.0254	7.4	7.3	7.5	7.3	7.3	7.36

Table 1.5 0.040" True Red fiber testing

True Red 0.040"						
Length (m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	AVG all Trials
40	204.8	200.1	196.1	203.4	199.9	200.86
35	163.2	162.2	161.8	167.1	168.6	164.58
34	178.8	175.9	172.2	169.8	168.7	173.08
33	186.5	172.5	184.4	183.4	182.1	181.78

Table 1.5 Cont.

32	171.1	170.3	169.4	169.1	168.8	169.74
31	203.2	204.7	204.4	204.1	203.7	204.02
30	204	203.5	196.7	188.3	182.4	194.98
29	178.5	167.4	164.8	170.2	169.3	170.04
28	167.4	168.2	167.3	166.8	167.4	167.42
27	169.3	162.4	164.5	157.8	160.1	162.82
26	148.5	155.8	159.9	146.7	149.3	152.04
25	168.7	166.6	165.5	165.2	164.6	166.12
24	207.4	205.1	205	204.3	203.7	205.1
23	167.2	166.6	165.4	164.6	168.3	166.42
22	156.6	152.3	149.8	155.2	151	152.98
21	144.4	162.7	146.8	152.1	147.6	150.72
20	173.3	170.1	170.6	168.8	168	170.16
19	145.6	149.8	139.2	135.3	138.3	141.64
18	140.1	138.2	155.6	157.8	139.8	146.3
17	162.3	140.3	166.4	145.5	169.7	156.84
16	147.8	157.3	127.5	138.2	126.5	139.46
15	139.4	130.3	148.7	160.3	168.1	149.36
14	150.1	120.9	124.9	132.3	170.2	139.68
13	203.3	201.1	199.9	196.5	194.3	199.02
12	187.3	180.1	152.1	150.4	145.3	163.04
11	142.2	142.5	150.3	140.1	143.3	143.68
10	166.7	170.5	166.9	166.2	170.9	168.24
9	161.8	160.5	160.2	160	159.7	160.44
8	160	158.8	158.4	156.2	155.3	157.74
7	142.1	134.8	132.6	130.4	130	133.98
6	141.9	141.3	140.2	139.2	137.8	140.08
5	136.2	135.5	134.7	134	133.7	134.82
4	120.2	118.7	118	122.2	119.6	119.74
3	136.4	136.3	136.6	136.3	135.6	136.24
1.016	112.5	117.6	110.8	109.9	108.6	111.88
0.762	107.9	105.6	104.4	104.2	103.8	105.18
0.635	112.7	109.5	107.4	106.9	106.7	108.64
0.508	98.3	97.5	96.1	95.6	94.7	96.44
0.381	75.7	76.8	75.2	74.8	74.3	75.36

Table 1.5 Cont.

0.254	62.3	61.8	62.6	61.8	61.5	62
0.127	55	56.1	56.4	56	56.1	55.92
0.1016	49	48.7	48.6	48.2	48.1	48.52
0.0762	46.1	46.2	45.8	45.6	45.3	45.8
0.0508	39.3	39.8	41	41.1	40.9	40.42
0.0254	21.8	21.2	21.3	21.2	21.8	21.46

Table 1.6 0.078" Yellow fiber testing

Yellow 0.078"						
Length (m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	AVG all Trials
0.889	532	494.6	571.6	462.3	435.7	499.24
0.762	412.3	496.6	504.1	479.9	482.3	475.04
0.635	478.3	490.2	446.5	479.1	517.9	482.4
0.508	344	272.6	315.4	327.3	375.5	296.76
0.381	330.4	278.9	268.8	266.5	339.2	326.96
0.254	311.9	276.8	288.1	308.8	316.6	300.44
0.127	164.7	139.8	150.1	123.4	163.5	148.3
0.1016	137.8	145.5	156.9	162.5	146.6	149.86
0.0762	120.5	106.4	129.7	118.8	119.5	118.98
0.0508	103.6	98.9	110	114.3	101.2	105.6
0.0254	43.4	58.6	46.7	61.5	53	52.64

Table 1.7 0.078” Orange fiber testing

Orange 0.078"						
Length (m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	AVG all Trials
1.016	276.4	223.5	282.7	249.6	256.9	257.82
0.889	255.3	285.6	268.2	274.3	236.4	263.96
0.762	135.6	149.7	132.2	151	151.1	143.92
0.635	130.3	152.2	135.6	152.3	131.1	140.3
0.508	121	127.5	136.4	122.6	130.8	127.66
0.381	129.7	118.1	137.8	119.8	120	125.08
0.254	135.4	112.1	135.3	107.3	109.3	119.88
0.127	135.1	123.6	113	100.1	101.2	114.6
0.1016	90.5	96.2	88.1	109.7	100.6	97.02
0.0762	99.3	91.9	98	100.4	95.4	97
0.0508	96	86.8	106.5	90.9	92.2	94.48
0.0254	70.4	79.8	72.4	78.5	83.2	76.86

Table 1.8 0.078” True Red fiber testing

True Red 0.078"						
Length (m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	AVG all Trials
1.016	239.8	230.8	219.7	237.3	229.3	171.82
0.889	193.2	172.8	154.4	168.7	170	173.62
0.762	165.3	171.6	182.7	184.8	163.7	163.9
0.635	162	154.8	168.3	166.3	168.1	173.62
0.508	164.2	153.1	151	158.4	151.1	155.56
0.381	138.4	147.8	133.5	137.5	140.4	139.52
0.254	123.7	154.8	111.7	132.2	171.8	138.84
0.127	159.6	145.1	141.9	143.1	143.8	146.7
0.1016	123.7	131.3	130.1	129.8	127.6	128.5
0.0762	57.7	56.3	57.4	11.1	63.2	49.14
0.0508	50.9	73.1	54.5	66.1	41.7	57.26
0.0254	33.4	52.3	47.9	41.3	39.5	42.88

Table 1.9 0.118" Orange fiber testing

Orange Red 0.118						
Length(m)	Trial 1	Trial 2	Trial 3	Trial 4	Trail 5	AVG all Trials
1.016	2429	2421	2419	2418	2418	2421.75
0.889	2199	2200	2198	2194	2199	2197.75
0.762	2139	2140	2150	2147	2151	2144
0.635	2124	2128	2120	2118	2123	2122.5
0.508	1999	1994	1993	1999	1992	1996.25
0.381	1789	1782	1784	1781	1778	1784
0.254	1537	1538	1539	1540	1539	1538.5
0.127	1139	1143	1142	1144	1146	1142
0.1016	999	1008	1005	1003	1006	1003.75
0.0762	814	818	819	816	815	816.75
0.0508	603.2	602.2	602.6	603.7	605.7	602.925
0.0254	455.8	455.6	456.7	456.8	456.9	456.225

Table 1.10 0.118" True Red fiber testing

True Red 0.118						
Length(m)	Trial 1	Trial 2	Trial 3	Trial 4	Trail 5	AVG all Trials
1.016	1343	1340	1338	1337	1330	1339.5
0.889	1329	1330	1332	1337	1335	1332
0.762	1330	1326	1321	1319	1321	1324
0.635	1298	1292	1304	1298	1290	1298
0.508	1270	1265	1262	1261	1269	1264.5
0.381	1229	1232	1234	1238	1240	1233.25
0.254	1227	1233	1230	1225	1228	1228.75
0.127	1111	1119	1120	1124	1108	1118.5
0.1016	1069	1071	1058	1050	1048	1062
0.0762	827	830	837	831	829	831.25
0.0508	679	680	675	680	676	678.5
0.0254	374.8	375.1	376.8	375.4	374.8	375.525

APPENDIX B

TABLE OF COLOR VERSUS COLOR

Table 1.11 Average current output (uA) radius 0.035" Orange versus True Red

Length(m)	True Red	Orange
1.016	112.8	93.14
0.889	112.05	85.6
0.762	107	80.96
0.635	98.825	80.22
0.508	92.7	78.44
0.381	89.675	77.48
0.254	75.85	71.26
0.127	46.375	51.92
0.1016	39.925	44.36
0.0762	36.3	37.16
0.0508	24.95	31.76
0.0254	14.125	17.8

Table 1.12 Average current output (uA) radius 0.040" Yellow versus True Red

Length (m)	Red	Yellow
40	200.86	415.8
35	164.58	317.7
34	173.08	318.12
33	181.78	318.88
32	169.74	375.16
31	204.02	294.94
30	194.98	267.3
29	170.04	225.56
28	167.42	222.12

Table 1.12 Cont.

27	162.82	227.82
26	152.04	226.42
25	166.12	223.34
24	205.1	222.3
23	166.42	226.02
22	152.98	215.66
21	150.72	208.42
20	170.16	210.06
19	141.64	197.58
18	146.3	183.62
17	156.84	177.56
16	139.46	182.58
15	149.36	185.44
14	139.68	168.38
13	199.02	166.78
12	163.04	161.16
11	143.68	152.96
10	168.24	154.06
9	160.44	150.36
8	157.74	146.94
7	133.98	137.3
6	140.08	133.24
5	134.82	137.3
4	119.74	122.48
3	136.24	116.38
1.016	111.88	107.26
0.762	105.18	102.04
0.635	108.64	99.84
0.508	96.44	85.44
0.381	75.36	79.58
0.254	62	61.22
0.127	55.92	37.08
0.1016	48.52	31.52
0.0762	45.8	26.06
0.0508	40.42	18.56
0.0254	21.46	7.36

Table 1.13 Average current output (uA) radius 0.078” Yellow versus Orange, and True Red

Length (m)	Yellow	True Red	Orange
0.889	499.24	173.62	263.96
0.762	475.04	163.9	143.92
0.635	482.4	173.62	140.3
0.508	296.76	155.56	127.66
0.381	326.96	139.52	125.08
0.254	300.44	138.84	119.88
0.127	148.3	146.7	114.6
0.1016	149.86	128.5	97.02
0.0762	118.98	49.14	97
0.0508	105.6	57.26	94.48
0.0254	52.64	42.88	76.86

Table 1.14 Average current output (uA) radius 0.118” Orange versus True Red

Length(m)	True Red	Orange
1.016	2421.75	1339.5
0.889	2197.75	1332
0.762	2144	1324
0.635	2122.5	1298
0.508	1996.25	1264.5
0.381	1784	1233.25
0.254	1538.5	1228.75
0.127	1142	1118.5
0.1016	1003.75	1062
0.0762	816.75	831.25
0.0508	602.925	678.5
0.0254	456.225	375.525

APPENDIX C

TABLE OF COLOR VERSUS RADIUS

Table 1.15 Yellow fiber comparison between radius 0.040” and 0.078”

Length(m)	0.04"	0.078"
0.889	107.26	499.24
0.762	102.04	475.04
0.635	99.84	482.4
0.508	85.44	296.76
0.381	79.58	326.96
0.254	61.22	300.44
0.127	37.08	148.3
0.1016	31.52	149.86
0.0762	26.06	118.98
0.0508	18.56	105.6
0.0254	7.36	52.64

Table 1.16 Orange fiber comparison between radius 0.035”, 0.078”, and 0.118”

Orange 0.035", 0.078", and 0.118"			
Length(m)	0.035"	0.078"	0.118"
1.016	112.8	257.82	2421.75
0.889	112.05	263.96	2197.75
0.762	107	143.92	2144
0.635	98.825	140.3	2122.5
0.508	92.7	127.66	1996.25
0.381	89.675	125.08	1784
0.254	75.85	119.88	1538.5
0.127	46.375	114.6	1142
0.1016	39.925	97.02	1003.75
0.0762	36.3	97	816.75
0.0508	24.95	94.48	602.925
0.0254	14.125	76.86	456.225

Table 1.17 True red fiber comparison between radius 0.035”, 0.040”, 0.078”, and 0.118”

True Red 0.035", 0.040", 0.078", and 0.118"				
Length(m)	0.035"	0.040"	0.078"	0.118"
1.016	93.14	111.88	171.82	1339.5
0.889	85.6	105.18	173.62	1332
0.762	80.96	108.64	163.9	1324
0.635	80.22	96.44	173.62	1298
0.508	78.44	75.36	155.56	1264.5
0.381	77.48	62	139.52	1233.25
0.254	71.26	55.92	138.84	1228.75
0.127	51.92	48.52	146.7	1118.5
0.1016	44.36	45.8	128.5	1062
0.0762	37.16	40.42	49.14	831.25
0.0508	31.76	21.46	57.26	678.5
0.0254	17.8		42.88	375.525

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