Improving Efficiency of a Solar Cell Using Optical Filters and Thin Films

W. Jackson Smith ‘19 and Hugh O. Thurman III

Department of Physics, Hampden-Sydney College, Hampden-Sydney, VA 23943

ABSTRACT

This experiment determined the efficiency of a single photovoltaic cell, and how the cell’s efficiency was altered after an optical filter and a thin film of laser dye was applied. An Arduino MEGA 2560 board was used to measure current and voltage and to calculate power through a C# code producing an IV curve on a graph in MakerPlot software. A directed light source was placed 40cm directly above the cell, and different intensities were tested to examine how varying intensities of the light source affected the cell’s performance. A simple circuit was constructed with a 1000Ω potentiometer so that the IV curve could be obtained. The optical filters that were used blocked out certain wavelengths of the light spectrum, attempting to optimize the specific range of wavelength that the cell harvests, or block out the wavelengths that damage the cell. The thin film that was applied to the cell was a Coumarin 460 laser dye that absorbs wavelengths of 300-350 nm and fluoresces in the range from 400-450 nm. Both methods attempted to optimize the visible light spectrum striking the solar cell to increase the overall efficiency. The laser dye proved to be extremely beneficial as both the current and voltage were increased on the IV curve of the cell, while efficiency was only altered about +/-3%. The main issue in this experiment was finding a way to create or find a light source that most accurately mimicked the Sun.

INTRODUCTION

The objective behind this experiment was constructing a simple, accurate, and quick way to calculate a photovoltaic cell’s efficiency so that a multitude of different alterations to the cell can be tested, deducing what increases efficiency of a PV cell. The United States used 97.7 quadrillion British thermal units (Btu) in 2017, and of that 97.7 quadrillion Btu, only 11% was renewable energy. Of the 11% of renewable energy, only 6% of it was solar energy, meaning only 0.66% of the United States energy consumption is from solar energy14. The importance of this issue is very relevant to today’s world as many scientists are working towards alternative energy sources so that fossil fuels aren’t such a necessity. Experiments similar to this one are becoming more prevalent, and research is expanding, ranging as far as constructing PV cells made up of organic compounds. One of the main interests in this field that scientists are looking at now is how to increase the lifespan of the PV cells, while still increasing efficiency. This research was created to find ways to increase efficiency of PV cell’s so that solar energy could become more useful. Solar energy is desirable for many reasons because, simply, it’s an alternative source of energy that is almost always present due to the Sun; however, there are some issues that hinder the ability to harvest solar energy, such as clouds and CO2 emissions that affect the amount of light that reaches the Earth’s surface. The rest of this paper discusses the theory behind this experiment, the method of experimentation, the analysis of results, and the improvements for further experimentation.

THEORY

Photovoltaic cells are semiconductor devices that produce a voltage when exposed to light and can generate current when connected into an electrical circuit. The current produced by a PV cell can be described by the following equation,

$$I = -I_{ph} + I_o\left(e^{\frac{q(V-IR_S)}{nkT}} - 1\right) + \frac{V-IR_s}{R_{sh}} \qquad (1)$$

where I is the current, Iph is the light-generated current, Io is the reverse saturation current of the cell, q is the electron charge, V is the voltage, Rs is the series resistance, n is the diode ideality factor, k is the Boltzmann constant, T is temperature, and Rsh is the shunt resistance. Io, n, Rsh, and Rs are the PV cell diode parameters. The performance parameters are also important when examining a PV cell, which include fill factor (FF), efficiency (η), short-circuit current (Isc), and open-circuit voltage (Voc). PV cell diode parameters are considered constant while performance parameters are intensity dependent. A simple, but useful equation for calculating the power output of a cell is described as the following,

$$P=IV \qquad (2)$$

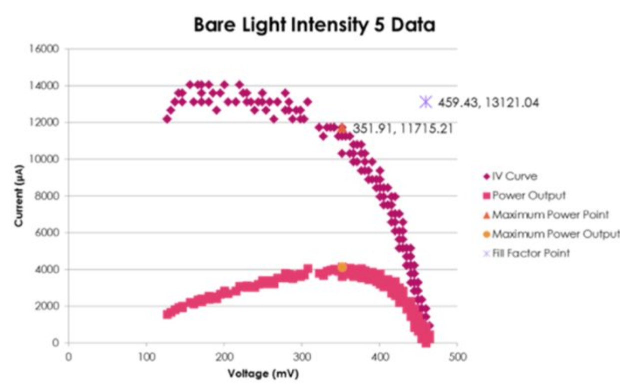
where P is power, I is current, and V is voltage. This equation is important because it is used in determining the efficiency of a cell, by calculating the maximum power point, which is the point on the IV curve when the value of P is the largest. The equation that is used to calculate the efficiency value, or Fill Factor, is the following,

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \quad (3)$$

where Vmp and Imp are related, representing the maximum power point on the IV curve, Voc is the open circuit voltage, and Isc is the short circuit current. This equation was the most used throughout the experiment, simply because it showed if the efficiency was altered by the optical filter, or thin film, during experimentation. However, the Eq. 1 was also very important in analysis because it shows how the parameters of the cell are operating.

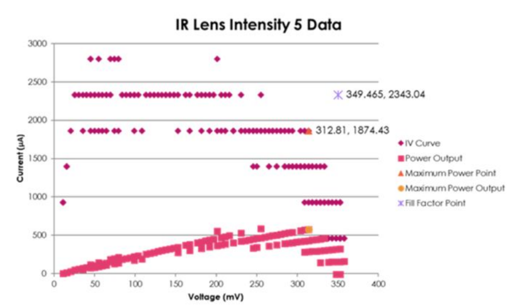
METHOD OF EXPERIMENTATION

The materials that were used to conduct this experiment included a breadboard, jumper wires, a 10Ω resistor, a 1000Ω potentiometer, light source, a stand with a clamp attached, a copper plate, six rare earth magnets, two pieces of plastic, a single photovoltaic cell, an Arduino Mega 2560, Arduino software, MakerPlot software, laser dye, infrared light filtering lens, and an Edmund Optics Bandpass filter kit #55-744. The copper plate, six rare earth magnets, two pieces of plastic, and the PV cell were all used together. The PV cell was place on top of the copper plate, which was used as the p-type conductive layer for the back of the PV cell. The two pieces of plastic were transparent, one being placed on top of the PV cell and the other being placed under the copper plate. The six magnets were then placed on either side of the two plastic pieces, three on the top and three on the bottom, to create a clamp so that the PV cell remained in a strong contact with the copper plate (see Image 1). The light source consisted of a stand with test tube holder to hold the focused light source in place (see Image 2). The breadboard, jumper wires, 10Ω resistor, 1000Ω potentiometer, the Arduino MEGA 2560, and the PV cell were used to create the circuit needed for the experiment. The 10Ω resistor was placed in the circuit simply for a safety precaution to limit current flow. Once the circuit was created, a code was written in C# using Arduino software to measure current and voltage and to calculate power simultaneously. The data collected from the code was transferred to the MakerPlot software to produce the IV curve. To conduct a data collection in this experiment, the light source would be on and placed 40cm above the PV cell. The potentiometer would begin at 0Ω to plot the Isc. Once the code was checked to make sure it was operating properly, MakerPlot was then checked to make sure it was plotting the data points correctly. Once everything was checked, the "on" switch was selected in MakerPlot to begin collecting data points. Then the potentiometer would be turned to increase resistance, increasing voltage and decreasing current, providing the IV curve on a graph. Once the Voc was obtained, the "off" button was selected to conclude the data collection. After the collection was finished, the maximum power point would be gathered from the data table, providing all the variables necessary to deduce the efficiency of the PV cell. This method was then repeated once an optical filter was placed in front of the light source, or once the PV cell was treated with the laser dye.

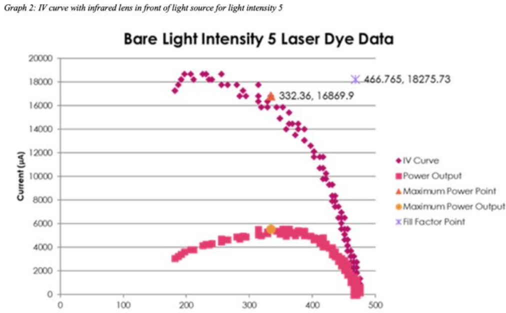


Graph 1: IV curve for control for light intensity 5

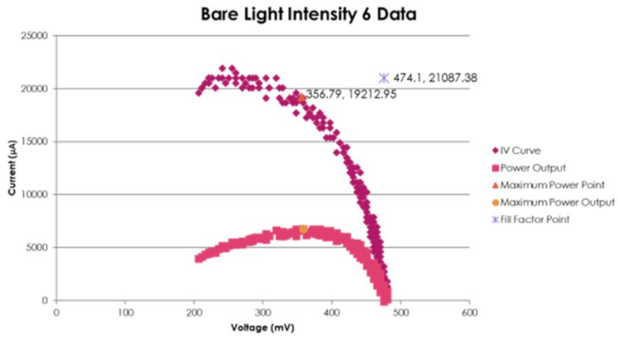
DATA



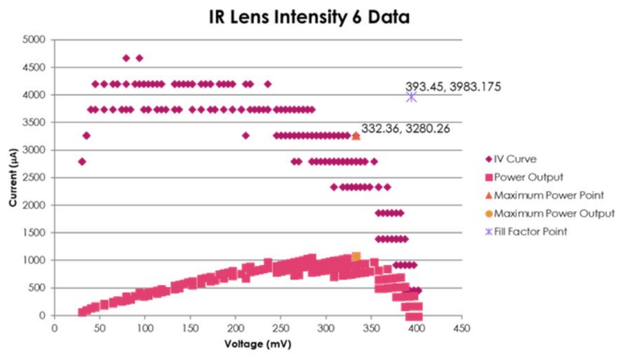
Graph 2: IV curve with infrared lens in front of light source for light intensity 5



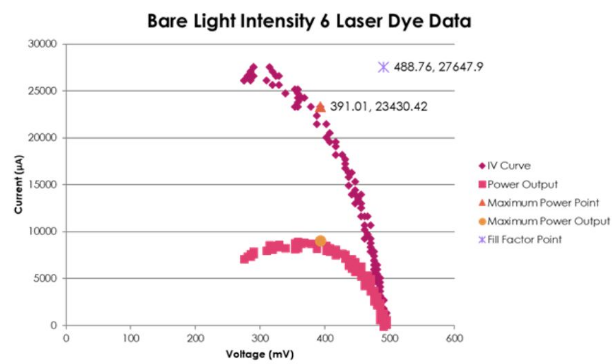
Graph 3: IV curve with thin film of laser dye for light intensity 5



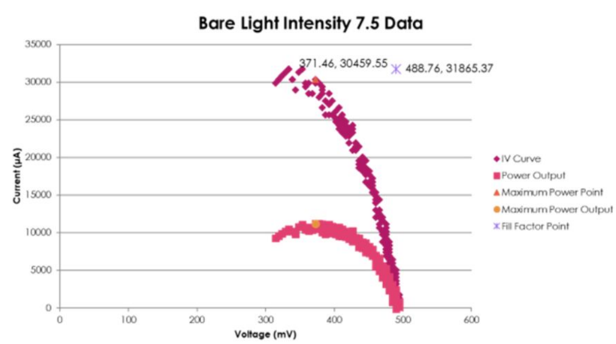
Graph 4: IV curve for control for light intensity 6



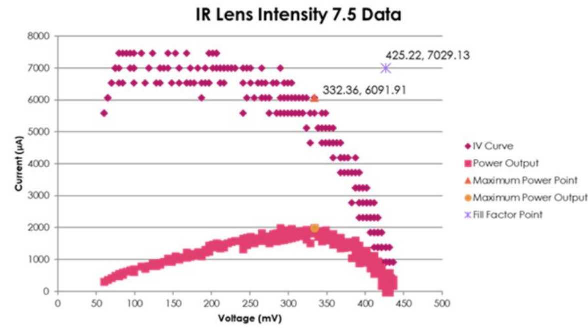
Graph 5: IV curve with infrared lens in front of light source for light intensity 6



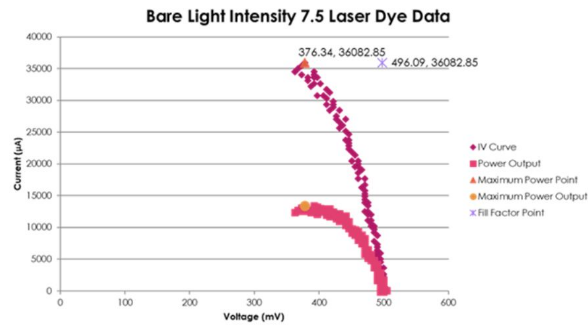
Graph 6: IV curve with thin film of laser dye for light intensity 6



Graph 7: IV curve for control for light intensity 7.5



Graph 8: IV curve with infrared lens in from of light source for light intensity 7.5



Graph 9: IV curve with thin film of laser dye for light intensity 7.5

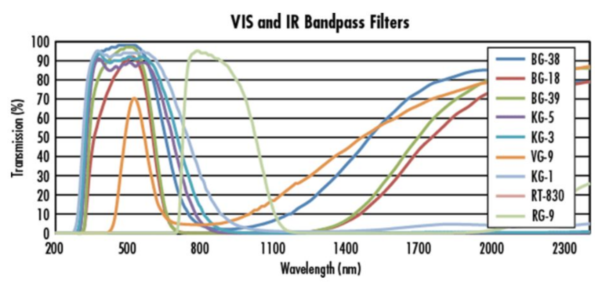
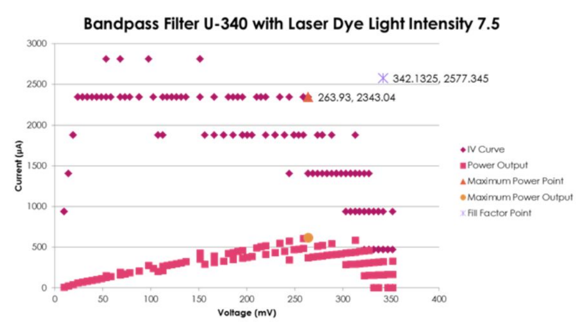
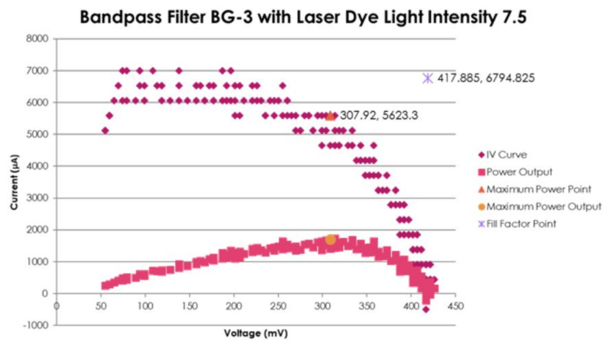


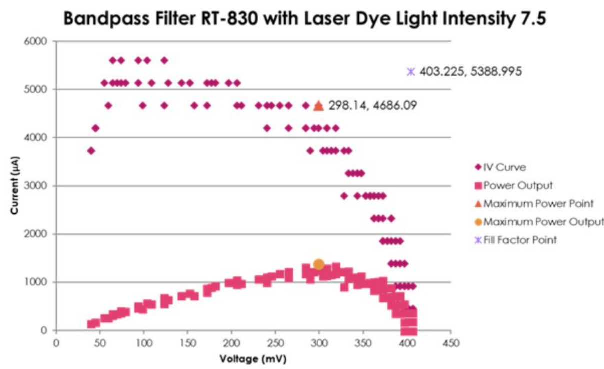
Figure 1: Graph showing optical filters effects after a light source passes through the filter



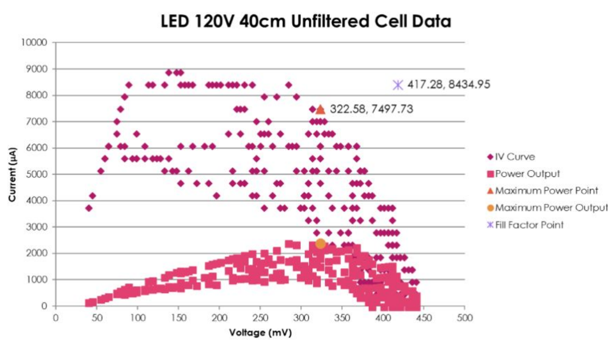
Graph 10: IV curve of Bandpass Optical Filter U-340 with thin film of laser dye for light intensity 7.5



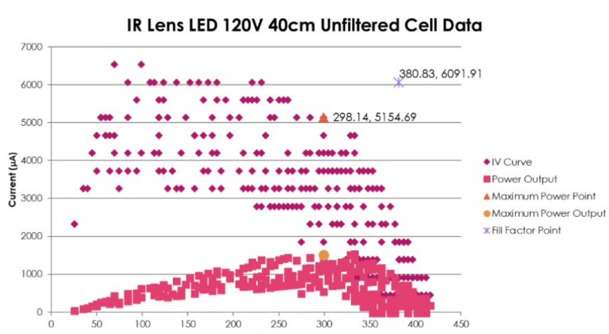
Graph 11: IV curve of Bandpass Optical Filter BG-3 with thin film of laser dye for light intensity 7.5



Graph 12: IV curve of Bandpass Optical Filter RT-830 with thin film of laser dye for light intensity 7.5



Graph 13: IV curve of control using a LED light source at 120V



Graph 14: IV curve with infrared lens in front of LED light source at 120V

Graphs 1-3 show the PV cell being tested with an incandescent bulb at light intensity 5. Graph 1 is simply the control so that the other data could be compared to it, providing a fill factor of 68.39%, or FF=68.39%. The data points on Graph 2 are a little splotchier, and both the current and voltage are extremely dampened, providing a FF=71.61%. The fill factor is higher in Graph 2 as compared to Graph 1, but the overall power output is significantly lower, showing that the IR lens is blocking out a large portion of useful light. In Graph 3, the data points come back together; however, the current is significantly increased, while the voltage is only slightly increased, providing a FF=65.73%. The results of Graph 3 are interesting because the thin film of laser dye clearly increases overall power output with a similar fill factor to Graph 1, proving that the effects of the laser dye absorbing wavelengths around 300-350 nm and fluorescing them in the range from 400-450 nm has a positive effect on the performance of the PV cell. Looking at Graphs 4-6 when the PV cell was tested with the incandescent bulb at light intensity 6, similar results were obtained. Graph 4 was simply the control for light intensity 6, providing a FF=68.57%. Again, when the IR lens was used for light intensity 6, as shown in Graph 5, the data points were slouchier than in the control, along with a severely dampened current and voltage, the overall power output was significantly decreased, providing a FF=69.57%. Similar to the comparison of Graph 1 and Graph 2, Graph 4 and Graph 5 show that the infrared lens is blocking out a large amount of light that could be harvested. When looking at Graph 6 with the thin film of laser dye on the PV cell, the current is increased significantly, while the voltage is barely increased, increasing the overall power output, providing a FF=67.80%. What is different about Graph 3 and Graph 6, with the differing light intensities, the IV curve in Graph 6 starts to slope downward almost immediately. The issue with the immediate downward slope in Graph 6 is that the short circuit current value may not be exactly accurate, altering the actual fill factor value. With Graphs 7-9 when the PV cell was tested with the incandescent bulb at light intensity 7.5, similar results from Graphs 1-3 and Graphs 4-6 were obtained; however, much like the issue in Graph 6, the IV curves in Graph 7 and Graph 9 slope downward immediately, meaning that the short circuit current value could be inaccurate. Graph 7 was simply the control for light intensity 7.5, providing a FF=72.65%. The results obtained in Graph 8 were very similar to the results found in the other graphs that were tested when using the infrared lens. Graph 8, when compared to Graph 7, had a significant decrease in current and voltage, overall significantly dampening the power output, providing a FF=67.74%. Much like explained above, a good portion of light that could be harvested was blocked out when using the IR lens. The infrared lens that was used dampened the current, voltage, and power too much to be considered a useful improvement for PV cells. The results in Graph 9, when testing the thin film of laser dye at light intensity 7.5, mimicked the results found in the other two graphs when testing the laser dye film. The current was increased significantly in Graph 9, while the voltage was slightly increased, increasing the overall power output, providing a FF=75.86%. The laser dye proved to be an interesting, but slight improvement to the PV cell; however, thickness of the film may have a large impact on how the cell performs, which, unfortunately, was not able to be measured in this experiment. Looking at Graphs 10-12, the Bandpass Optical Filters did not prove useful. Fig. 1 shows the effects of some of the optical filters, simply for reference. The optical filters were tested on light intensity 7.5, and when Graphs 10-12 are compared to the control of Graph 7, the optical filters significantly dampened current, voltage, and power, showing that they would not be of any use to increase efficiency. Graph 10 provided a FF=70.13%. Graph 11 provided a FF=60.98. Graph 12 provided a FF=64.29. Only three out of the eight optical filters from the Edmund Optics Bandpass Filter Kit #55-744 provided results; however, there are other optical filters that come in different Edmund Optics Bandpass Kits that could have been more useful, but they were unable to be tested. The last two graphs provided used a different light source in hopes to more accurately mimic the Sun, and also to simulate differing heat effects on the PV cell. For Graph 13 and Graph 14 a focused LED bulb was used. Graph 13 is simply the control for the LED light source at 120V, providing a FF=68.72%. Graph 14 examined the results of placing the infrared lens in front of the LED bulb at 120V, providing a FF=66.24%. Unlike the other graphs that tested the effects of the IR lens, Graph 14 didn't experience the same drop in current or voltage. The reason that the LED bulb had similar results with and without the IR lens is because the LED bulb didn't heat up the PV cell, and because the LED bulb didn't range as far into the infrared spectrum, which is more accurately mimicking the sun. Each fill factor, or FF, was calculated using Eq. 3. It is worth noting that the fill factors of each graph are not entirely accurate if they were scaled up to a module, a configuration of single PV cells, but the fill factors of the graphs did provide a constant so that differing results could still be analyzed.

DISCUSSION

The focus of this research was to improve the efficiency of a photovoltaic cell. The first objective was to construct a method to efficiently obtain accurate readings of current, voltage, and power from the PV cell using an Arduino MEGA 2560 with a code written in C#. Once data was collected, the focus was then shifted to creating IV curves with the collected data, which was achieved by using MakerPlot software. The next step was examining the effects of treating the PV cell with a thin film of Coumarin 460 laser dye and filtering the light that reached the PV cell by using optical filters. The last objective of this experiment was altering the light source to more accurately mimic the Sun. When testing with the incandescent bulb at light intensity 5, the control had a FF=68.37%, the infrared lens in front of the light source had a FF=71.61%, and the thin film of laser dye had a FF=65.73%. When testing with the incandescent bulb at light intensity 6, the control had a FF=68.57%, the infrared lens in front of the light source had a FF=69.57%, and the thin film of laser dye had a FF=67.80%. When testing with the incandescent bulb at light intensity 7.5, the control had a FF=72.65%, the infrared lens in front of the light source had a FF=67.74%, and the thin film of laser dye had a FF=75.86%.When testing with the incandescent bulb at light intensity 7.5 with the optical filters, Bandpass Filter U-340 with thin film of laser dye had a FF=70.13%, Bandpass Filter BG-3 with thin film of laser dye had a FF=60.98%, and Bandpass Filter RT-830 with thin film of laser dye had a FF=64.29. When testing with the LED bulb at 120V, the control had a FF=68.72% and the infrared lens in front of the light source had a FF=66.24%. Some improvements that could be made to this experiment would be finding a way to accurately determine the thickness of the film of laser dye to get a better idea of what the optimal thickness is. Another improvement would be discarding some graphs that have an inaccurate short circuit current due to the immediate downward slope; however, using the LED bulb at 120V seemed to eliminate that issue. Moving forward in this research field, testing different laser dyes, or a combination of them, could prove beneficial. Another improvement would be testing exactly which portion of the light spectrum the laser dye absorbs and fluoresces would be useful to understand.

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