Methods for Characterizing a Variety of Common Diodes

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A discussion of the simulation results for an ideal diode lead into the methods of characterization for a wide range of PN junction diodes and their applications. A P6KE6.8 diode is used to observe how the IV curve of a real diode deviates from ideal diodes and then the capacitance of its depletion region is measured as a function of DC offset. A FDS100 photodetector is put to the test to learn about its behavior as a photovoltaic device and its intended operation in reverse bias where it was found to be linearly proportional to the intensity of incident light. A set of 3 LEDs were characterized by measuring their spectral intensity as a function of driving current, and their wavelengths were found to be $\lambda_{blue} = 473.37 \pm 1.42$, $\lambda_{green} = 556.91 \pm 2.88nm$, $\lambda_{red} = 627.96 \pm 3.47nm$. A red Sanyo DL-3148-025 Laser Diode was used to determine the relationship between output wavelength and driving current which showed a linear relation, and the slope efficiency was found to be $194.5\frac{counts}{mW}$.

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1. CHARACTERIZATION OF COMMON DIODES

The study of electronic circuits typically begins with an introduction to Ohm's Law which relates the voltage drop across a resistor to the current through it as a linear function, $V = IR$. Further down the line of studying electronics comes the topic of capacitors and their differential relationship with current which is, $I = C\frac{dq}{dt}$. When this circuit component is used alongside a resistor there are some interesting properties of non-linearity which need to be addressed, especially when considering alternating current (AC) signals. This document will address the non-linearity of a device called a diode which exhibits the characteristics of a resistor and a capacitor, so these elementary concepts will be reviewed.

A. The PN junction Diode

An ideal diode is meant to operate as a simple switch, where voltage applied from one direction results in a current passing through the device and the opposite directional current is blocked. It is one of the most fundamental circuit elements that exhibits non-linearity [1], and a common schematic involving the device can be seen in Fig. 6.

A simulation of the generic circuit shown in Fig. 6 can be run with LTSpice XVII to characterize the I-V curve for an ideal or a non-ideal diode. Kirchhoff's circuital law says that the current entering a junction must be equivalent to the current exiting the junction, and is truly just a restatement of conservation of energy. Regardless, this law can be utilized to say that the current through the resistor will be equivalent to the current through the diode. So by measuring the voltage drop across the resistor as well as the diode, and using Ohm's law to determine the current through the resistor the diode I-V curve can be found. The results of the simulation can be seen in Fig. 1, when the device is run in reverse bias there is no current which could be considered an off state of a switch. When a forward bias if placed across the diode a non-linear increase in the current is observed until the device starts to asymptote around $0.7V$.

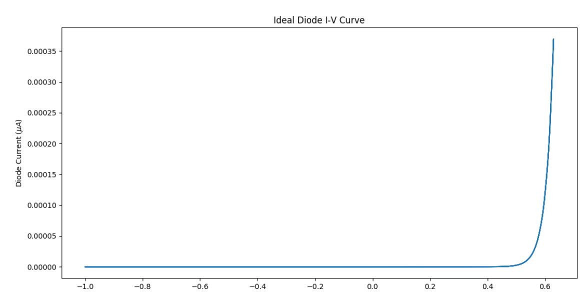

Fig. 1. I-V curve for an ideal diode. When run in reverse bias there is no current through the device, but when run in forward bias the device allows current to flow in a non-linear fashion and asymptotes at a DC bias around $0.7V$.

The diodes which are dealt with in this document are either PN or P-i-N semiconductor diodes. These devices consist of either p-type and n-type semiconductors in direct contact or sep-

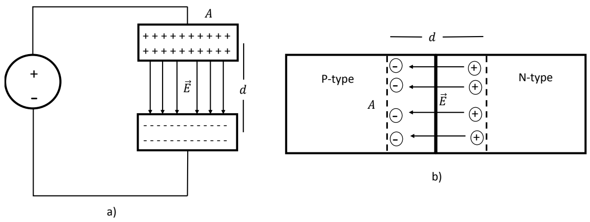

Fig. 2. Diagram of similarities between a) a parallel plate capacitor, and b) a PN junction diode. In equilibrium the charge carriers diffuse through the interface and cause an electric field across the depletion region which is between the dashed lines.

arated by a small region of an intrinsic semi-conducting material. When these doped regions are placed in contact the charge carriers (holes and electrons) will diffuse through the interface and recombine to form a depletion region [2]. The depletion region will have a net neutral charge, while the edges on the p-type or n-type sides will have free charges form along the surface. The geometry of the system begins to look like that of a parallel plate capacitor as shown in Fig. 2. Due to the capacitive nature of the depletion region, the circuit shown in Fig. 6 can be approximated as an RC circuit under certain conditions. The capacitance is inversely related to the distance of the charged plates, $C = \frac{Q}{d}$, so when the diode is under forward bias and the depletion region decreases the resultant capacitance should increase. In a generic RC circuit, the reactance of a capacitor can be expressed $X_C = \frac{1}{\omega C}$ where ω is the angular frequency at which the voltage is being oscillated [3]. The summation of the circuital components is $Z = R - iX_C$ so the gain can be solved with Ohms law as,

$$\frac{V_{out}}{V_{in}} = \frac{iX_C}{R + iX_C} = \frac{iX_C(R - iX_C)}{R^2 + X_C^2} \tag{1}$$

The real part of Eq. 1 describes the amplitude of the gain while the complex part expresses the phase. Looking solely at the real part, the capacitance can be solved for in the following form.

$$C = \frac{1}{\omega R}\sqrt{\left(\frac{V_{in}}{V_{out}}\right)^2 - 1} \tag{2}$$

Equivalently the width of the depletion region in forward bias is expected to decrease as a function of bias voltage. This lower separation between capacitive plates results in an increase in the capacitance.

A.1. Characteristics of the P6KE6.8 Diode

The circuit shown in Fig. 6 was constructed on breadboard with a 991Ω resistor and P6KE6.8 diode in series. A Rigol DG4162 Function Generator was used to bias the circuit with a $10kHz$ ramp function with minimum voltage of $-7V$ and maximum voltage $1V$. A Rigol DS1102E oscilloscope was used to capture the voltage across the resistor and diode simultaneously. From Kirchhoff's current law, the current through the resistor must be equivalent to the current through the diode so capturing the voltage across the resistor and using Ohm's law allows the

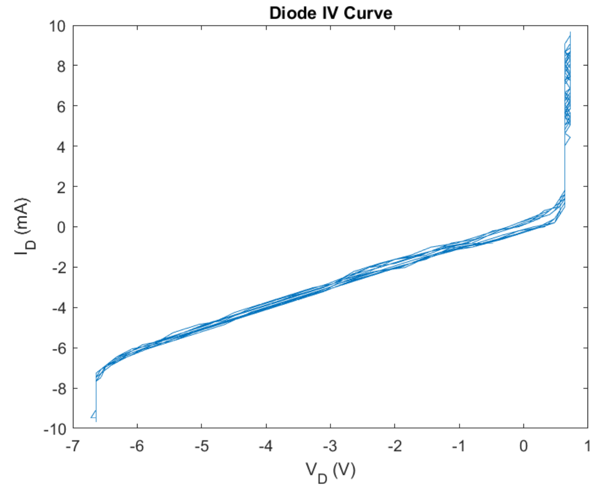

Fig. 3. IV Curve for P6KE6.8 diode. The function deviates from that of the ideal PN junction diode in the reverse bias region, and the current asymptotes around a forward bias voltage of $0.7V$.

current through the diode to be known. The output waveforms were captured on USB and MATLAB17 was used to solve for the current and plot the resultant IV curve which is shown in Fig. 3. In forward bias the current reaches an asymptote around $0.7V$ where the diode turns on and lets current through as if the device were a short circuit. In reverse bias the diode decays linearly until about $6V$ where the breakdown voltage is observed and the current in the reverse direction asymptotes in a similar fashion to the forward bias region.

The same circuital setup was used to measure the capacitance of the diode as a function of DC offset. The capacitor in general behaves like a DC stop for AC circuits, which means that any DC offset from an input signal won't propagate through the rest of the circuit. A $10kHz$ sinusoidal voltage was applied to the resistor by the function generator and the oscilloscope was set to measure the RMS voltage across the diode. The input signal was then modulated by hand to apply a DC offset to the sinusoidal input in increments of $20mV$ from $0V$ to $8V$. The capacitance was found with Eq. 2 and the results shown in Fig. 4 were plotted with Python.

The curve shows the capacitance increasing as a function of the offset voltage. There seems to be a region below an offset voltage of $1.5V$ where the capacitance is constant, but then it starts to increase exponentially and then approaches a linear function. The increase makes sense because the DC offset will be shrinking the depletion region of the junction which means the thickness gets smaller which will make the capacitance increase.

A.2. Characteristics of the FDS100 PIN Photodiode

Another method for making diodes is to add a layer between the p-type and n-type regions which contains only the intrinsic material. This layer acts as a permanent depletion region and is expected to have similar characteristics to the generic PN junction, but is better for use in high voltage circuits [4]. In this case a FDS100 PIN photodiode was characterized instead of a P6KE6.8 in the circuit schematic shown in Fig. 6. The photodiode is made with a clear pane of glass over the semiconducting substrate to allow photons to be incident on the device. When photons are incident on the depletion region, there is a probability for an

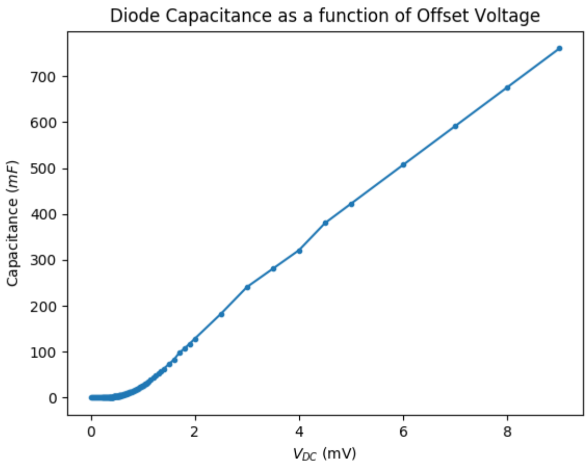

Fig. 4. Calculated capacitance of P6KE6.8 Diode as a function of DC offset voltage applied to an input sinusoidal waveform. The curve shows a region of exponential increase which tends toward a linear increase.

electron and hole to be created and the pair can either recombine or be swept away by an electric field to measure a current. The diode was covered in order to prevent light from interacting with the substrate, the resistor was swapped for one with value $5.53k\Omega$ and a $1kHz$ ramp function was swept from $-5V$ to $1V$. The resultant IV curve can be seen in Fig. 5, where the current was found by measuring the voltage across the resistor and the voltage was found across the photodiode. The waveforms were captured with the oscilloscope and the data analysis was performed in MATLAB17. The photodiode is designed for high voltage applications, and in this particular case the device is meant to be reverse biased and allow a current flow which is proportional to the amount of light that is incident on its surface. Thus there is a region of large reverse bias where the device doesn't asymptote as the P6KE6.8 diode did, but there is still an asymptotic region in forward bias.

B. Light Emitting Diodes

The light emitting diode (LED) is a device which is meant to operate inversely to the photodiode in the sense that it is meant to emit light as a current is passed through the semiconductor. The main process which lead to the emission of light from the diode is known as electroluminescence where charges are forced into the semiconductor causing recombination to occur and charges move from higher energy states into lower energy states by emitting photons [5]. Light emitting diodes have a seemingly infinite number of applications and the characterization of these devices is important for understanding their uses and limits.

B.1. Coupling an LED and Photodiode

To determine which LEDs were operating properly a $10k\Omega$ resistor was placed in series with an individual diode similar to the setup shown in Fig. 6 but the AC signal was replaced with a constant $7V$ DC bias. If luminescence was observed the diode was considered operable and was used in further characterization experiments. The FDS100 photodiode was designed for a wavelength of light around $630nm$ so a suitable clear capped red LED was chosen to be coupled with the photodiode. A mask of tape was used to collimate the light from the top of the LED

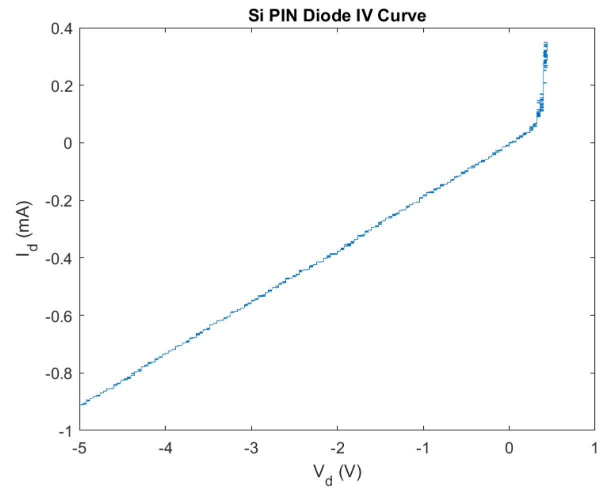

Fig. 5. IV curve for the Silicon PIN photodiode. An IV curve similar to that shown in Fig. 3 arises, but there is no asymptote in reverse bias.

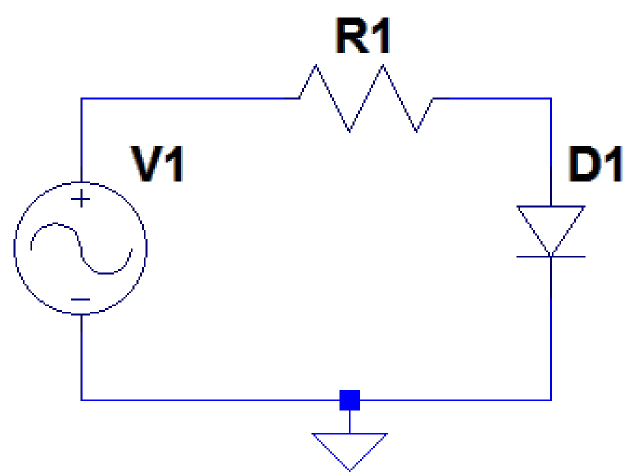

Fig. 6. Generic Circuit Schematic for a diode and resistor in series. The diode is labeled D1 and is being biased by an AC voltage source labeled V1. This circuit schematic was made with LTSpice XVII.

directly into the photodetector by wrapping it around a few times to create one compact coupled device similar to a photoresistor. Once the device was constructed it was placed into the circuit shown in Fig. 7 where $R_1 = 10k\Omega$ and $R_2 = 5.3k\Omega$ and the voltage across the LED and photodiode were allowed to vary and in some scenarios R_2 was removed from the circuit altogether.

B.2. Photovoltaic operation

To see how the photodiode operates as a photovoltaic device, the power into the LED was calculated by measuring the voltage across the $10k\Omega$ resistor and applying the well known equation $P = \frac{V^2}{R_1}$ and the voltage across the photodiode was measured with the oscilloscope. The relation between the output power from an LED and the light intensity is linearly proportional to the area of the device [6], so assuming that the output power efficiency of the LED is also linearly proportional to the input power the power should be related to that of the resistor. The results of this experiment are shown in Fig. 8 where the voltage across the photodiode is constant until around $250\mu W$ and then it increases linearly with voltage. A $7V$ ramp function of frequency $1kHz$ was used to bias the LED circuit and the oscilloscope was used to measure the voltage across the diode.

B.3. Short circuit mode

A 10Ω resistor was placed into the circuit shown in Fig. 7 and the oscilloscope was used to measure the voltage across that passive device. The current was calculated using Ohm's Law and the same oscilloscope, and the same $7V$ ramp function was used to bias the LED. The addition of a 10Ω resistor means the device wasn't completely in short circuit mode, but the value is very small and can effectively be ignored. The results are shown in Fig. 9 where the current through the diode follows the same basic pattern as the voltage where it remains constant until about $250\mu W$ before increasing linearly with input intensity. Both the data analysis for this section and the previous were performed using MATLAB17.

B.4. Reverse Bias

To find how the photodiode reacts to an optical input while in reverse bias, the circuit schematic shown in Fig. 7 was constructed with a $10k\Omega$ resistor in series with the LED and either no load resistor or a $5.3k\Omega$ resistor in series with the photodiode. A $-6V$ DC bias was applied to the photodiode to make the device operate in reverse bias, and the input voltage to the LED was varied from 0 to $10V_{DC}$. The voltage across the LED was measured with a FLUKE 179 digital multimeter, and the current through the photodiode was measured with a Keithley 175 Auto-ranging Multimeter. The reverse bias IV curve can be seen in Fig. 10 where the current has a constant value until the LED voltage gets to about $2V$ where it produces enough light to cause carriers in the depletion region to move to higher energy states and current can begin to flow. The magnitude of the current increases linearly with the increase in voltage across the LED.

B.5. LED Optical Power and Photodiode Rise Time

Another interesting characteristic of an LED is its output power which was measured with a COHERENT Laser Power/Energy meter. A red LED was placed in series with a $10k\Omega$ resistor and a Keithley ammeter as the bias was varied across the entire circuit. A plot of the LED power can be seen in Fig. 11 where the output power seems to increase quadratically as a function of the driving current, which is similar to the output power

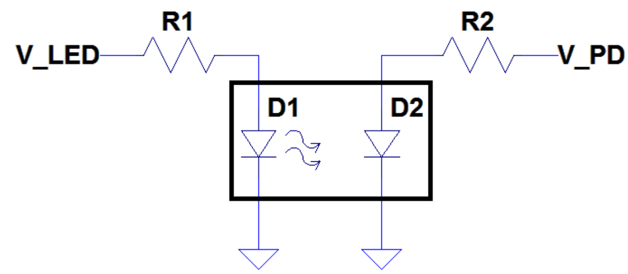

Fig. 7. Circuit diagram for LED coupled with FDS100 Photodiode. The diode labeled D1 is the LED while that labeled D2 is the photodiode.

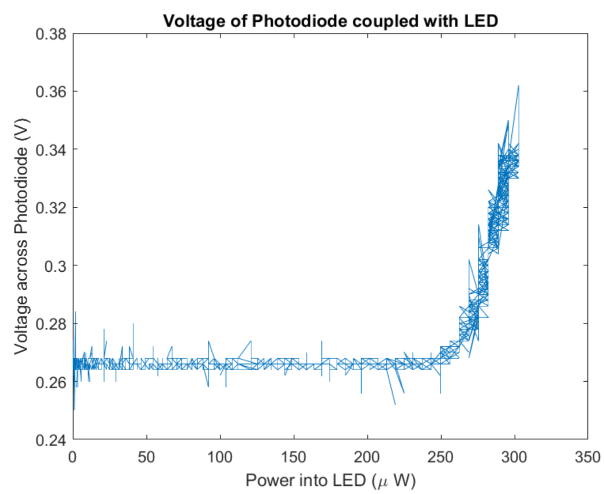

Fig. 8. Voltage of photodiode coupled with LED in photovoltaic mode. The voltage across the diode is constant until an LED input power of about $250\mu W$ where the voltage increases in a linear fashion.

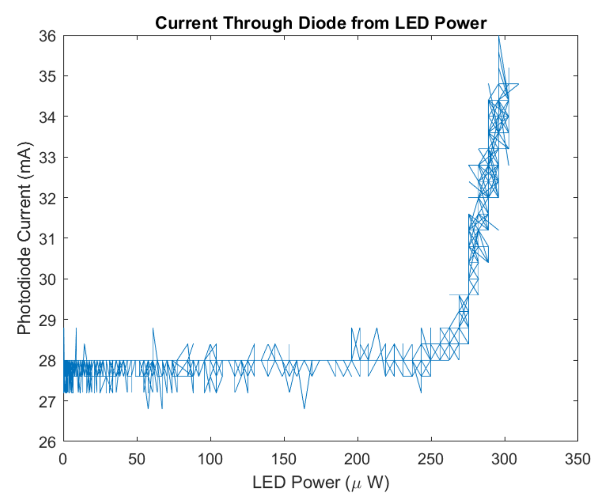

Fig. 9. The short circuit current through the photodiode which was coupled with a red LED. The current mimics the voltage in photovoltaic mode where it is constant until around $250\mu W$ and then increases linearly with LED input power.

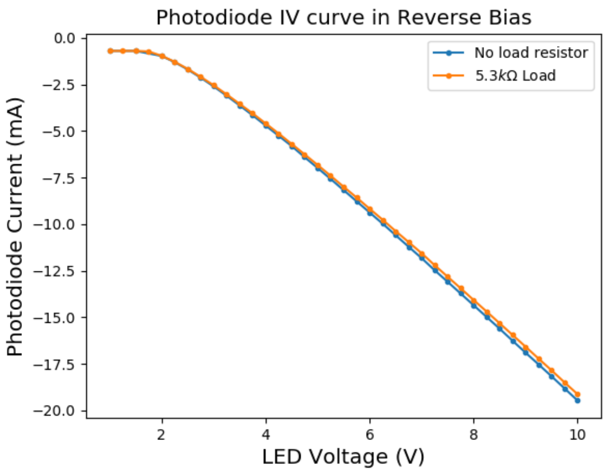

Fig. 10. IV curves for the FDS100 Photodiode while run in reverse bias under no load resistance and load resistance of $5.3k\Omega$. The magnitude of the current increases linearly after biasing the LED half of the circuit with $2V$.

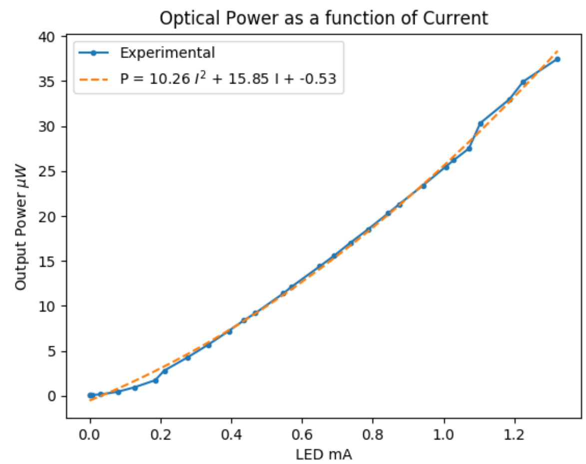

Fig. 11. The output power from a Red LED as a function of the driving current. A quadratic function has been fit to this experimental data.

of a resistor. A polynomial fit was applied with the assistance of the numpy polyfit function in Python, and the coefficient for the quadratic term came out to be slightly above 10 which corresponds to the resistance in series with the diode and shows that there is a relation between the power output of the resistor and the diode.

Quickly looking back to the capacitive aspects of the PN junction, when a square waveform is placed across an RC circuit the device will slowly build charge on the capacitive plates. The rate at which it charges or discharges is inversely proportional to the capacitance, so by determining the rise time and knowing the resistance the capacitance can be solved for. The general relation for the capacitor voltage can be found from Kirchhoff's circuital laws [7] as,

$$\frac{V_{out}}{V_{in}} = \left(1 - e^{-\frac{t}{RC}}\right) \tag{3}$$

$$C = \frac{-t}{R\ln\left(1 - \frac{V_{out}}{V_{in}}\right)} \tag{4}$$

To explore this more, a $10kHz$ square waveform was used to drive an LED in series with a $10k\Omega$ resistor and an oscilloscope was used to measure the voltage change across the FDS100 photodiode which was in series with a $5.3k\Omega$ resistor. A single instance of the output voltage can be seen in Fig. 12 which has the same the general voltage profile of a capacitor in an RC circuit as was hypothesized. The time which took the diode rise to half its saturation value was about $0.3604ms$, so the capacitance can be solved for using Eq. 4.

$$C = \frac{-0.3604ms}{(5.3k\Omega)\ln\left(1 - \frac{1}{2}\right)} = 98nF$$

This capacitance value is significantly lower than those which were found in Fig. 4 which lends to the idea that there were some unit conversion issues during earlier experiments. Or that the depletion region of the PIN diode is much larger than that of the P6KE6.8 diode since there is an inverse relationship between the capacitance and the depletion. That would make sense because the addition of the intrinsic region should add some thickness to the overall depletion region.

2. INTENSITY AND SPECTRA FOR LEDS AND A LASER DIODE

Many passive circuit components are very cheap and easy to replace, but there are some devices that are unique and some are impossible to replace. So special circuits have to be constructed to guarantee that sensitive components won't be destroyed by large current or power outputs. One way to achieve that is with a regulator which is incorporated into a circuit as shown in Fig. 13. With this circuital configuration a series of LEDs and a Laser Diode can be characterized with the certainty that the devices won't have too much current pass through them. The circuit was constructed with a LM317 regulator, a 27Ω resistor, a $10\mu F$ capacitor, a P6KE6.8 diode, and the linear $1k\Omega$ potentiometer from a Global Specialties PB-505 bread board. To test that the circuit was working, a red LED was placed in the circuit at $D2$ and a $7V_{DC}$ source was used to bias the design. Rotation of the potentiometer and the modulation of the intensity of the light out of the diode confirmed that the circuit was operational and ready for use.

A. Measuring LED Light Intensity

There were three LEDs (Red,Green, and Blue) which were characterized with assistance from the regulator circuit. One end of an optical fiber which was connected to an Ocean Optics HR2000+ High Resolution Spectrometer was positioned above the LED with assistance from an optical mount. The LED was set to output the highest amount of light possible by turning the potentiometer to allow the largest current to flow, once this was achieved the fiber optic was placed in a location where the maximum intensity wasn't over saturated on the Ocean Optics software which analyzed the intensity and wavelength of the beam incident on the fiber optic. The mount was used to keep the fiber static and guarantee that the only variable which was being changed to achieve a different intensity was the current through the diode. By varying the current through the diode by rotating the potentiometer and capturing the spectra as determined by

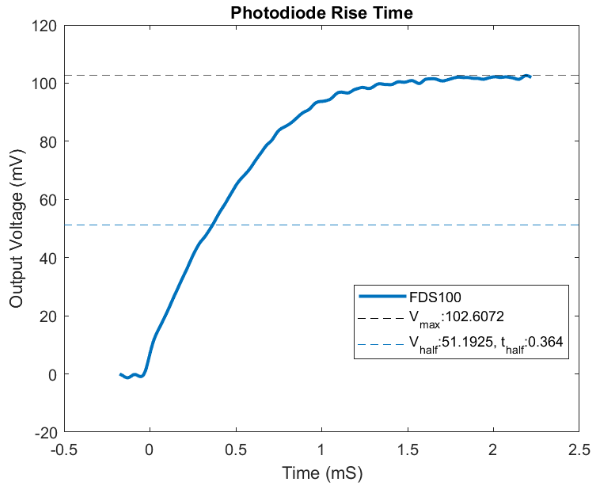

Fig. 12. Rise time of the FDS100 Photodiode when biased by a $10kHz$ square wave. The maximum voltage was around $100mV$ and the time at which the voltage was half its maximum was $0.364mS$ after being triggered.

the Ocean Optics hardware and software, a relationship between the Intensity of light for the three different LEDs as a function of their driving current was found and is shown in Fig. 16. From the Ocean Optics software, the average central wavelengths for the LEDs were: $\lambda_{blue} = 473.37 \pm 1.42$, $\lambda_{green} = 556.91 \pm 2.88nm$, $\lambda_{red} = 627.96 \pm 3.47nm$.

Each of the intensities increase as a function of the driving current and they appear as if they begin to saturate as the current increases. The position of the spectrometer for the three different LEDs was not consistent so it is inconclusive to determine whether one color of LED produces more power than the other, for that a more consistent setup for the positions and saturation levels of the LEDs would be needed. Also it should be noted that even though the fiber optic was positioned so that it would be able to view the maximum intensity of the devices without saturating there were issues with the stage being bumped and translated which positioned the device in a location where it ended up saturating at lower driving currents for the blue and green LEDs. This method of characterization would significantly benefit from a more stable design, potentially a printed circuit board could be developed for the regulator circuit and LEDs or other optical devices could be plugged in as desired. This PCB could then be mounted in a convenient geometry which is less susceptible to mechanical noise which would lead to more accurate measurements of intensity and spectra.

B. The Laser Diode

Using the same circuital setup as shown in Fig. 13 and discussed in Sec. A, the LED was replaced with a red Sanyo DL-3148-025 Laser Diode. An optical mount with a larger base was used to hold the optical fiber spectrometer and this was taped down for added stability. The laser diode was then set to a maximum current value and the position of the fiber spectrometer was chosen to maximize the amount of intensity without saturating the device to allow for maximum resolution of intensity and wavelength. To measure the input power to the laser diode a Fluke digital multimeter was used to measure the voltage across the device while a Keithley multimeter was used to measure the current through the device. The same Ocean Optics devices and

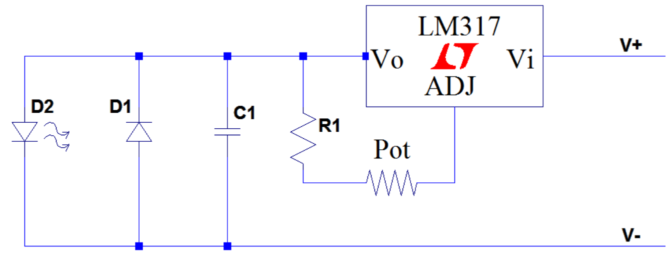

Fig. 13. Circuit diagram for the regulator circuit which was built to control the amount of current allowed to move through LEDs and a Laser Diode.

software were used to measure the output intensity which is proportional to the output power by a factor of the area of the luminescent portion of the diode.

The results of this characterization experiment are shown in Fig. 15 where the center wavelength of the red laser diode is increasing linearly as a function of the driving current. This is an interesting phenomenon, and is very important to consider when designing an ordinary laser. If the current into the laser wanders too far from a steady state value the output wavelength from the laser diode will wander as well which could potentially interrupt the ability to lase in devices whose cavities are very wavelength sensitive.

Determining the slope efficiency of the laser is a relatively simple process which requires knowledge of the input and output power of the device. The input power is found as the product of the voltage and current across and through the laser diode respectively, and the output power is proportional to the output intensity as was discussed previously. The results of this can be seen in Fig. 16 where the output intensity increases linearly with the output power, and a linear fit has been performed in Python to get a slope of $194.5\frac{counts}{mW}$. The diameter of the effective window for the diode is about $1.6mm$ and in theory the output power could be calculated, but the strange unit of counts which was given by the Ocean Optics software isn't easy to translate directly into mW to give the actual efficiency of the diode. Potentially there is a way to have the software relate the intensity of light incident on the fiber to a power per unit area which would be more conducive to finding the actual slope efficiency.

3. CONCLUSION

This document focused on the physics and characterization of a handful of different PN junction diode devices. A simulation of an ideal diode was created to show that the diode acts as an electrical switch. A discussion of the capacitance of a diode from the depletion region led to a direct derivation of the diode capacitance as a function of the DC offset which was applied to an AC source. From these simple discussions and derivations a P6KE6.8 diode was able to be characterized by obtaining the IV curve and capacitances at varying DC offsets.

After gaining an elementary understanding of generic diodes there was a more directed study into the applications of optoelectronic diodes such as photodiodes and LEDs. An FDS100 photodiode was characterized for its properties as a photovoltaic device, and it was even shown to behave in a linear fashion when run in reverse bias and illuminated with photons from a coupled

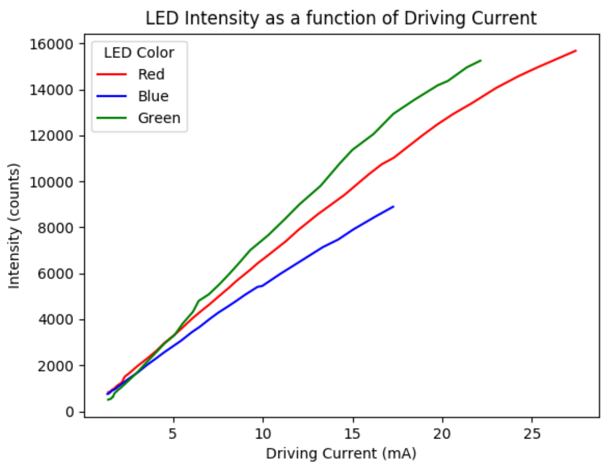

Fig. 14. Intensities of three separate LEDs as a function of the driving current. Each intensity increases with the driving current and they all seem to begin to saturate. The blue and green LEDs began to saturate the spectrometer.

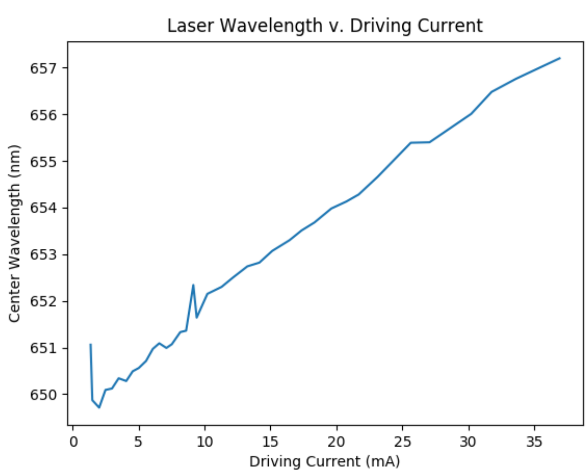

Fig. 15. The wavelength of the red laser diode as determined by the Ocean Optics hardware and software. The wavelength increases nearly linearly with the driving current.

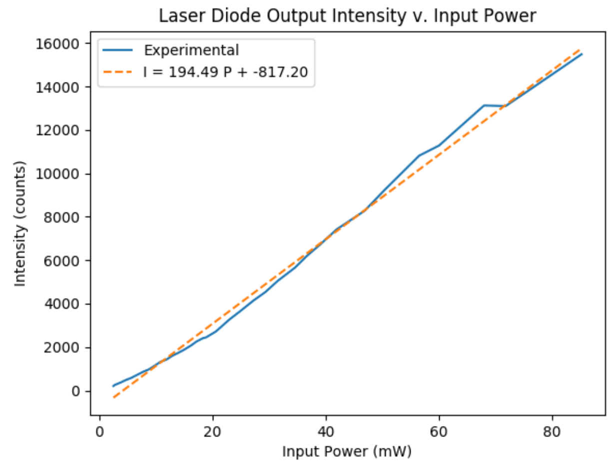

Fig. 16. The output intensity of the laser diode as a function of the input power. The slope efficiency is shown as the dashed linear fit which was performed in Python.

LED.

After thoroughly exploring the photodiode, a regulator circuit was built to create a constant current through an LED. This current was then altered to obtain the relationship between the LED output intensity as a function of driving current for three different LEDs. They all showed a region of linearity before beginning to saturate at higher currents. After ensuring that devices were not being destroyed within the regulator circuit, a laser diode was replaced in order to be characterized. The wavelength of the laser diode was measured as a function of the driving current and it was determined that there is a linear relationship between the driving current and the laser diode wavelength which is of particular interest to individuals who are designing lasers. It was also seen that the output intensity of the laser diode was linearly proportional to the input power to the laser diode and a slope efficiency was found to be $194.5\frac{counts}{mW}$. Overall this was a very successful laboratory and characterization session, many devices were analyzed without destroying a single component.

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