Lab III - Diodes

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1 Introduction

Up to this lab the focus has been on analyzing and constructing linear circuits. In this lab we attempt to delve into the much richer topic of nonlinear circuitry, which plays an important role in modern electronics. Since nonlinear elements are by definition nonlinear they are much more difficult to analyze than their linear counterparts. Thus, in this lab we attempt to learn several techniques in analyzing and predicting the effects of such elements. In particular, this lab focuses on the diode which is important for rectiftying the output signal of a circuit. Utilizing various techniques including graphical load line analysis and perturbation analysis, we can apply linear circuit theory and thus determine the outputted signals. Although these techniques are applied to only diodes in this lab, they can be used when dealing with arbitrary nonlinear circuitry, and thus will be important in future labs.

2 Problems

3.1 : Using the DMM we measured the resistance of a 1N4448 diode. By attaching the red minigrabber end to the diode anode and the black end to the cathode, we measured a resistance of 638Ω (which corresponds to a .638 V forward voltage drop). Swapping the positions of the minigrabber ends, the DMM outputted that the resistance was off the scale and therefore a negligible amount of current was flowing through the diode. This confirmed that the diode conducts unidirectionally.
3.2 : Using a plastic-stick-mounted 1N4448 diode we repeated the measurements in 3.1. Like before, we found that no current flowed when the red minigrabber end was attached to the diode cathode and that the diode had a $0.640V$ forward voltage drop (which is very similar to what we measured in 3.1) when the red minigrabber end was attached to the diode anode.

When the diode is heated, we would expect its forward voltage drop to decrease, and likewise when it is cooled, its forward voltage drop should increase. This was confirmed when we pinched the diode (thus heating it up) and measured the forward voltage drop to be $0.622V$ and then cooled it (by dipping it in liquid nitrogen), obtaining a forward voltage drop of $1.060V$.

3.3 : Adjusting the Offset Adjust knob, we found that the voltage outputted by the offset adder can range from $-8.67V$ to $8.67V$. By loading the output with several resistor values, and by applying Ohm's Law ($V_{out} = I_{out}R$), the V-I curve in Figure 1 was produced. It is clear that for output currents less than roughly $24mA$, the output voltage is directly proportional to current and the circuit is relatively stiff.

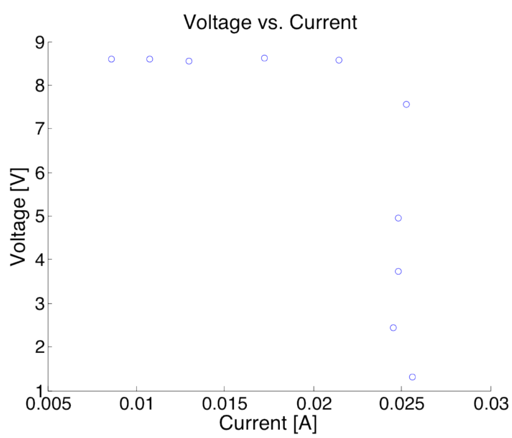

Figure 1

3.4 : Using the circuit shown in Figure 2, we varied the voltage across the diode using the offset adder. The characteristic curve (measuring the current versus the voltage) is plotted in Figure 3 using a normal linear plot and Figure 4 using a log-linear plot.

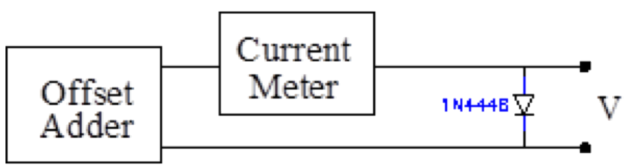

Figure 2

3.5 : Using the curve tracer we obtained the characteristic curves for the diode (without the stick), the diode mounted on a stick at room temperature, and the diode mounted on a stick immersed in liquid nitrogen, which are shown in Figure 5, Figure 6 and Figure 7, respectively. Note that the characterstic curve of our diode is superimposed with the data obtained using the current meter.

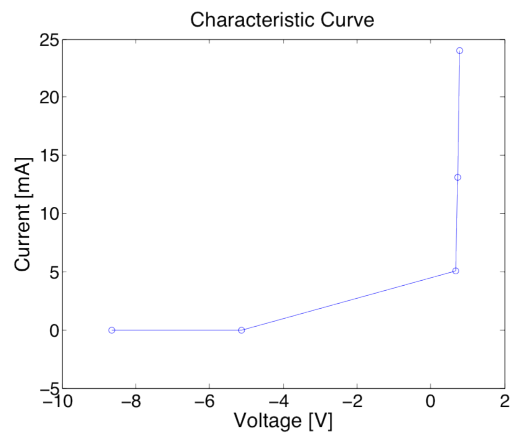

Figure 3

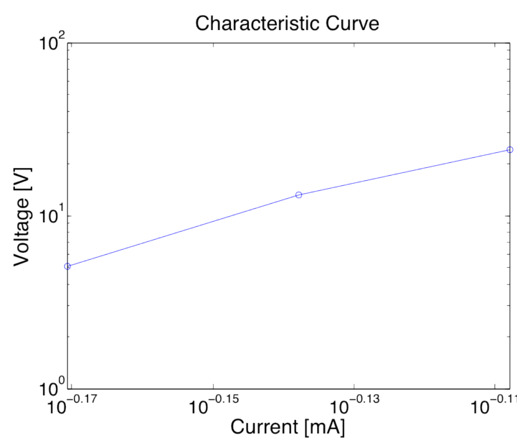

Figure 4

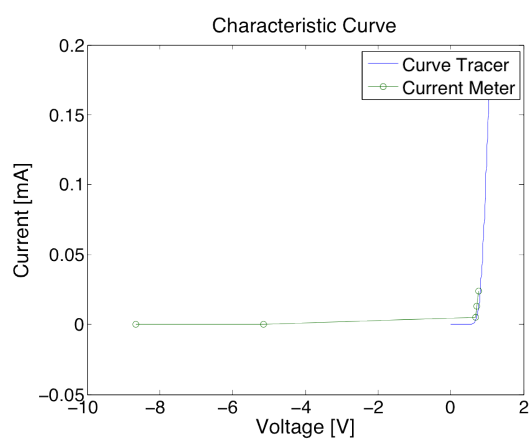

Figure 5

For the diode on a stick, we measured the saturation current to be $i_{sat} = 3.73 \times 10^{-9} A$ and the

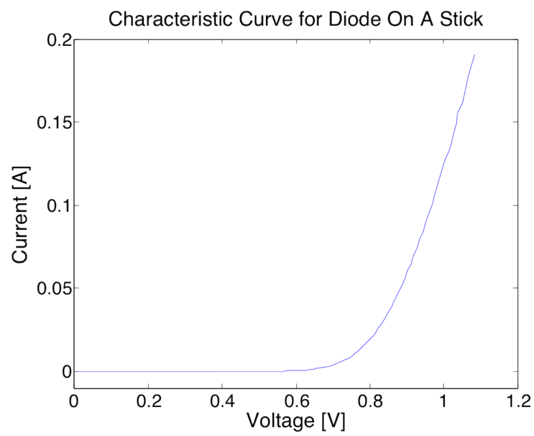

Figure 6

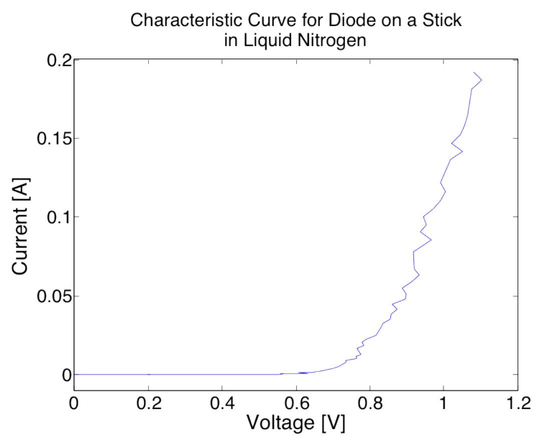

Figure 7

voltage coefficient to be $V_{coeff} = 19.80$. Likewise, when the diode on a stick was immersed in liquid nitrogen these values were found to be $i_{sat} = 8.48 \times 10^{-29} A$ and $V_{coeff} = 19.80$. Since

$$V_{coeff} = \frac{e}{nKT} \tag{1}$$

When the diode on a stick was at room temperature, we computed n to be 2.02, and when the diode was immersed in liquid nitrogen the measured values was 2.77.

3.6 : After constructing the circuit shown in in Figure 8, the voltage across the resistor was measured to be 9.3 mV. Since the diode is in series with the resistor, then current flowing through both elements must be equal. Thus, by Ohm's Law the current flowing through the diode was

$$I_{throughdiode} = \frac{V}{R} = \frac{9.3mV}{10^6\Omega} = 9.3 \times 10^{-6} mA \tag{2}$$

3.7 : The half-wave rectifier circuit shown in Figure 9 was constructed. The input AC voltage

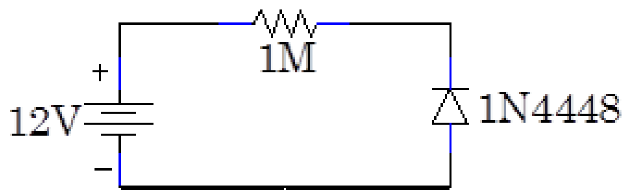

Figure 8

(dark blue) can be seen superimposed on the circuit output (torquise) in Figure 10.

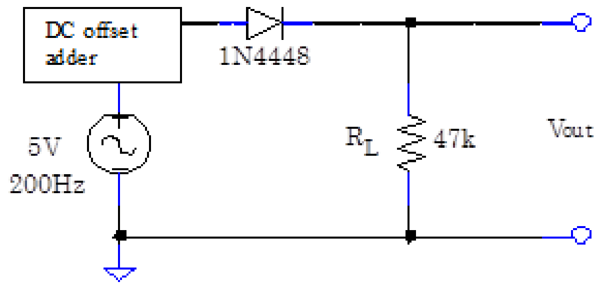

Figure 9

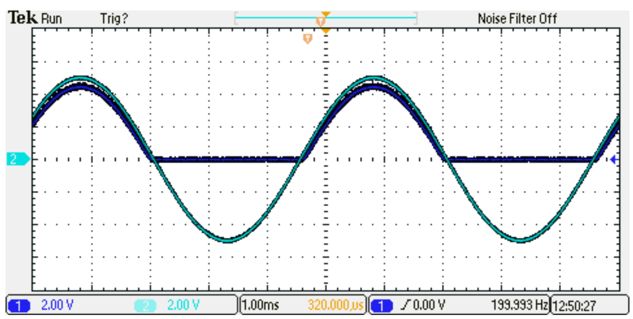

Figure 10

The dark blue curve shows the sinusoidal AC source voltage. The turqoise curve shows the circuit output. Since the diode does not allow current to flow when it is negatively biased, there is no outputted current when the source voltage is negative. In addition, note that there is a small (roughly 0.5 V) difference in the peaks of the source voltage and circuit output. This is a consequence of the voltage drop of the diode when it is forward biased.
3.8 : Next, the circuit shown in Figure 11 was constructed. The input AC voltage (dark blue) is shown superimposed on the output voltage in Figure 12. The $1\mu F$ capacitor allows charge to be stored while the input voltage is positive (and current is passing through the diode). Thus, when the input voltage is negative (and no current is flowing through the diode) the charge flows out of the capacitor smoothing out the output signal. Note that even with the addition of the capacitor there is still a little ripple in the signal. By doubling

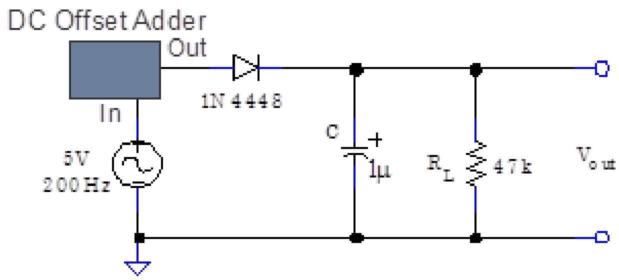

Figure 11

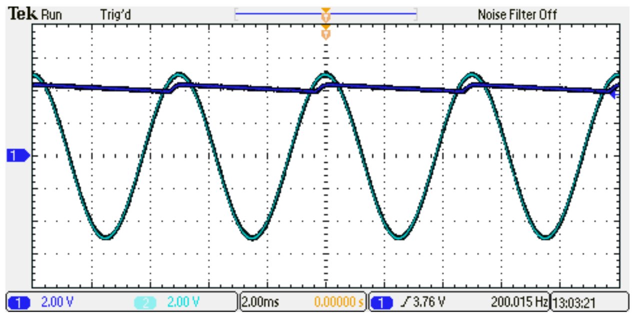

Figure 12

the input frequency, the ripple decreases in size since there is less time for the capacitor to discharge (shown in Figure 13).

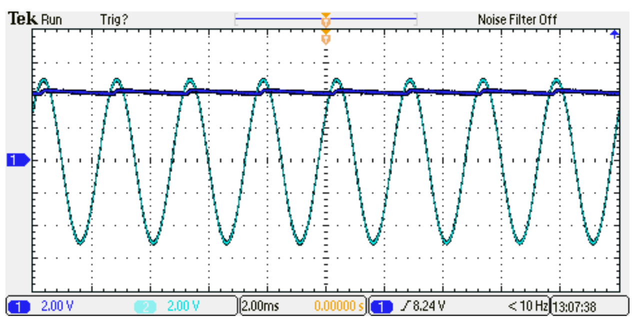

Figure 13

Doubling the capacitance decreases the size of the ripple since more charge is stored by the capacitor (when the input voltage is positive), allowing it to produce more current when the input AC voltage is negative (shown in Figure 14) . Doubling the resistance has the same effect as doubling the capacitance (as seen in Figure 15) . These three effects will be confirmed in the analysis in 3.15.

3.9 : The circuit shown in Figure 16 was built. Using resistances of $1k\Omega$ and $10k\Omega$ for $R1$ the input voltage was varied from $0.25V$ to $2V$. The peak-to-peak output voltages are shown in Table 1 and Table 2. Next, a graphical load line analysis for the $1k\Omega$ and $10k\Omega$ resistors is shown in Figures 17 and 18, respectively. Since the x-values of the intersection of the load

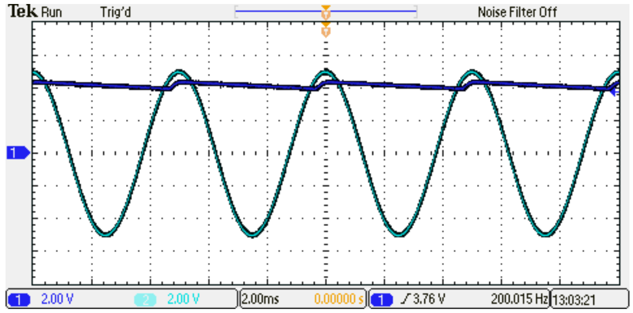

Figure 14

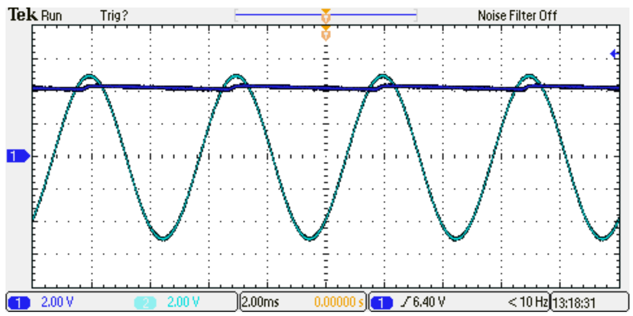

Figure 15

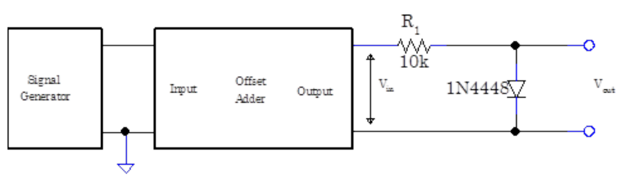

Figure 16

line and characteristic curve determine the output voltage, it is clear that the measure values are very close to what would be expected.

3.10 : When a signal is connected to the Offset Adder's Input BNC, the Adder's output is simply the sum of the input signal and the internal voltage offset set by the Offset Adjust knob. Thus, turning the knob simply increases or decreases the signal by a constant voltage.

3.11 : Using the signal generator, a 0.1 V p-p sine wave was inputed to the Offset Adder which was set to a +1 V DC offset. Reconnecting the 10k resistor and diode to the Offset adder, the outputted signal was seen to be a sine wave (not rectified) shifted by $1V - 0.05V = 0.95V$. The lower half of the signal was cutoff in 3.7 because the input voltage was at times negative and thus no current would flow. However, with the addition of the offset adder the input voltage (the sum of the AC voltage and the offset adder voltage) is always positive. Thus current will flow through the diode and the output signal will not be rectified as can be seen in Figure 19.

3.12 : By decreasing the DC offset the AC component of the output signal increases. This

Table 1: 1 $k\Omega$

V_{in}	V_{out}
0.25 V	0.249 V
0.5 V	0.458 V
0.7 V	0.526 V
1.0 V	0.572
2.0 V	0.628

Table 2: 10 $k\Omega$

V_{in}	V_{out}
0.25 V	0.242 V
0.5 V	0.395 V
0.7 V	0.436 V
1.0 V	0.47
2.0 V	0.518

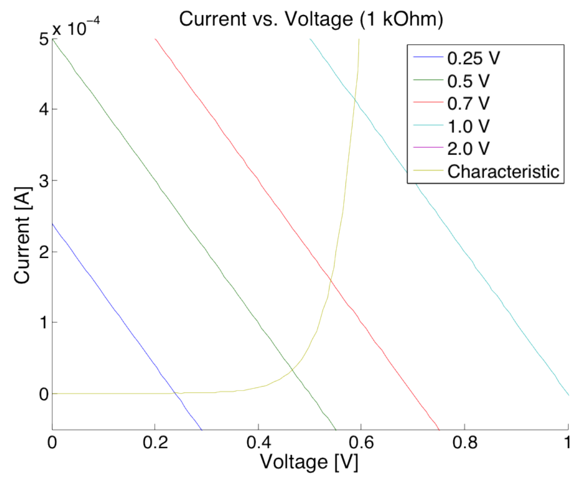

Figure 17

can be seen in Figure 20.

3.13 : The circuit shown in Figure 21 was constructed, where the diode used was an LED. As expected, for any diode no current will pass through the circuit and therefore the LED will not light. Swapping the power supply polarity the voltage drop across the LED was measured to be 3.599 V and the voltage across the resistor was measured to be 1.506 V. Next, the resistor was varied and the corresponding voltages measured across the resistor and LED are shown in the following table.

As the resistor value is increased,the voltage drop across the resistor increases and the forward voltage drop across the LED decreases (since the total voltage drop must remain constant).

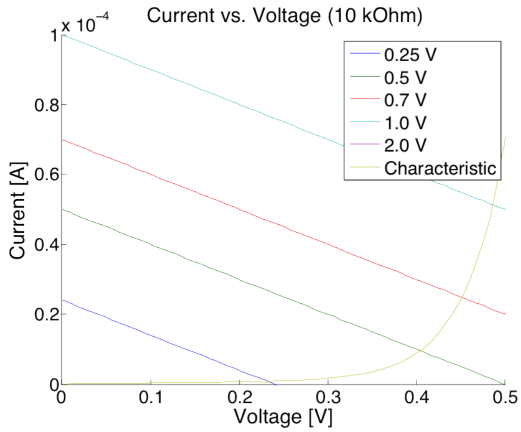

Figure 18

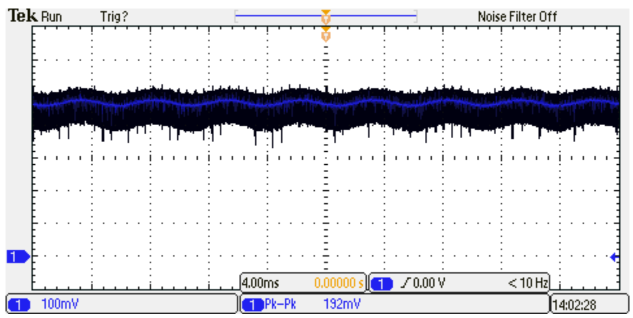

Figure 19

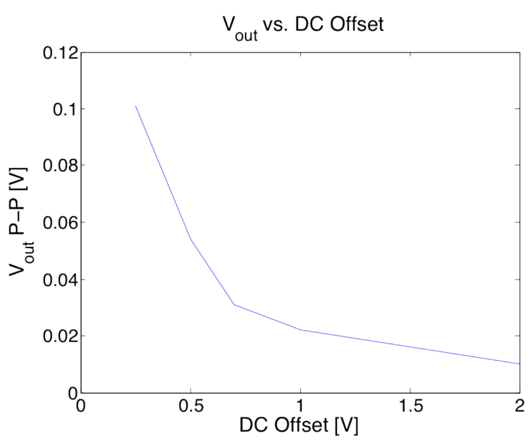

Figure 20

Thus, less power is dissipated by the LED, and the LED appears dimmer.

3.14 : Figure 22 displays the characteristic curve of the LED measured using the Curve Tracer.

3.15 : Consider the circuit built in 3.8. When the AC voltage is positive, the capacitor will

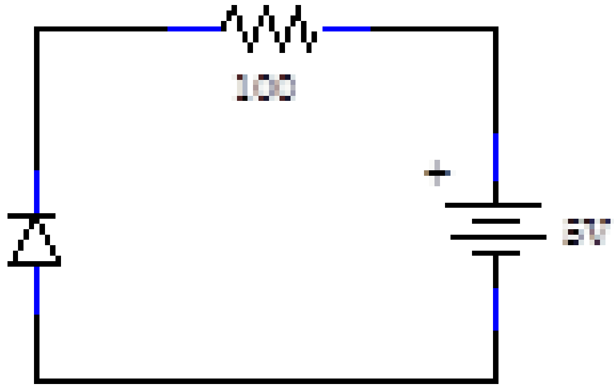

Figure 21

Resistor	Voltage Across Resistor	Voltage Across LED
300 Ω	1.763 V	3.339 V
3 $k\Omega$	2.056 V	3.039 V
30 $k\Omega$	2.328 V	2.760 V
300 $k\Omega$	2.631 V	2.451 V

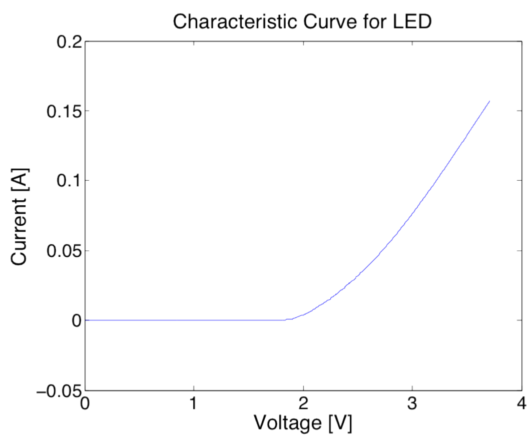

Figure 22

charge until it reaches a potential V_0. As the AC voltage becomes negative, the capacitor will discharge and the voltage across can be modeled as

$$V(t) = V_0 e^{-t/\tau} \tag{3}$$

where $\tau = RC$. Letting V_r be the voltage difference of the ripple, we know that at the end of a period

$$V_0 - V_r = V(T)$$
$$V_0 - V_r = V_0 e^{-T/\tau}$$

Therefore, $V_r = V_0(1 - e^{-T/\tau})$. Assuming that the time it takes the capacitor to discharge is much longer than the period, then we can approximate $e^{-T/\tau}$ to first order in T/τ as

$$e^{-T/\tau} \approx 1 - \frac{T}{\tau} \tag{4}$$

Hence,

$$V_r \approx V_0 \left(\frac{T}{\tau}\right) = \frac{V_0}{fRC} \tag{5}$$

where $f = 1/T$ is the frequency of the AC voltage. This equation agrees with the measurements performed in 3.8. In particular, doubling the frequency, the resistor value or the capacitor value should approximately halve the size of the ripple.

3.16 : For this problem, we focused on performing perturbation analysis with DC Offsets of 0.2 V, 0.5 V and 1 V. Since the AC voltage had an amplitude of 0.05 V, by linearizing the diode characteristic around the operating point, we can find the intersection of this tangent line with the loadlines at the DC offset plus and minus 0.05 V. The difference between the x-values of these intersections should produce an estimate for the peak-to-peak voltage of the AC signal. The plots describing showing the loadlines and diode characterstics are shown in in Figure 23 (0.2 V), Figure 24 (0.5 V),and Figure 25 (1 V).

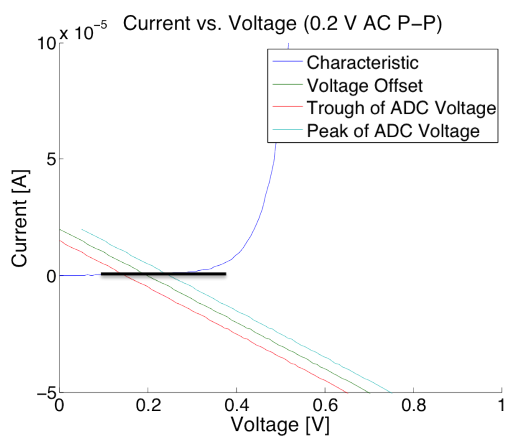

Figure 23

The values we obtained for the AC voltages were $0.95V$ (for 0.2 V), $0.025V$ (for 0.5 V), 0.015 (for 1 V). All of these values are within a factor of 3 of what we measured in 3.12.

3.17 : By producing a tangent line at the operating points of the values we computed the resistance of the diode at those points to be $1.76M\Omega$ (for 0.25 V), $6.06k\Omega$ (for 0.5 V), and 733Ω (for 1 V).

Using the voltage divider equation $V_{out} = \frac{Z_{diode}}{R+Z_{diode}} V_{in}$ where $R = 10k\Omega$ and V_{in} is the voltage of the AC input signal (which is $0.1V$), then we find V_{out} for the Plotting these on the

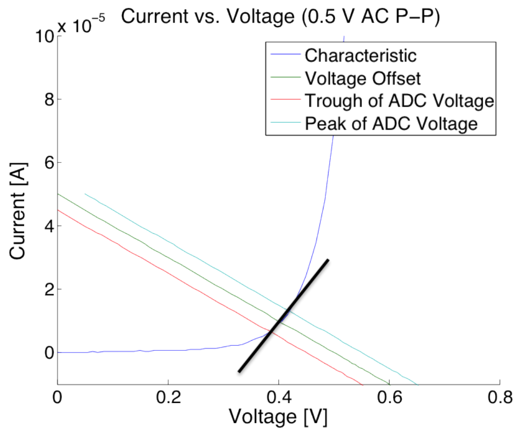

Figure 24

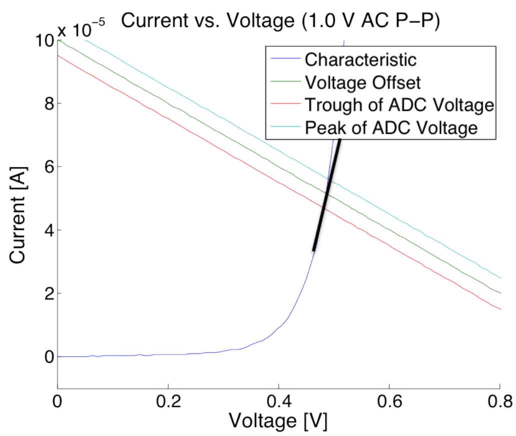

Figure 25

same graph as Figure 20, we see that that these calculated values are on the same order of magnitude as the measured values (shown in Figure 26).

A large AC signal corresponds to large perturbations. In Figure 27, we see that the actual resistances of the diode at the peaks and troughs of the signal are no longer well-approximated by the the resistance value at the DC offset. Using the tangent line, we would compute the outputted sigal to have a peak-to-peak voltage given by the difference in the dark blue lines, while the actual peak-to-peak voltage is given the red lines. Since the red lines are closer together than the blue lines, the large signal impedance would produce a value much greater than what we might measure.

DC Offset	Z_{diode}	V_{in}	V_{out}
0.25 V	1.76 $M\Omega$	0.1 V	0.099 V
0.5 V	6.06 $k\Omega$	0.1 V	0.038 V
1.0 V	733 Ω	0.1 V	0.0068 V

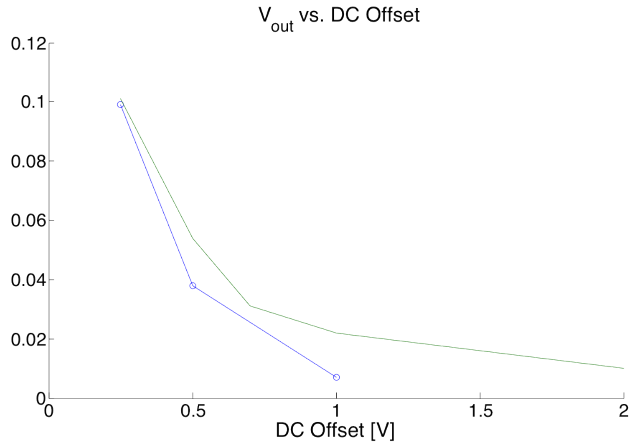

Figure 26

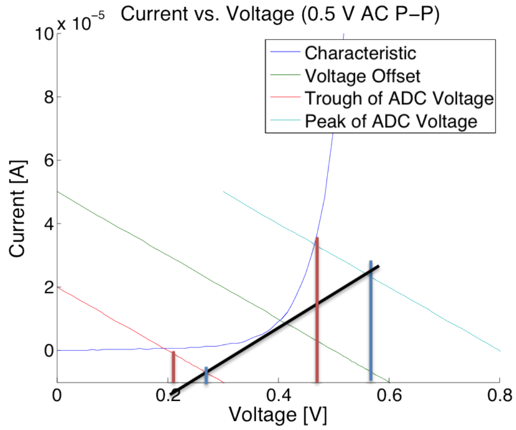

Figure 27

3.18 : The characteristic curve of the Zener diode is shown in Figure 28.

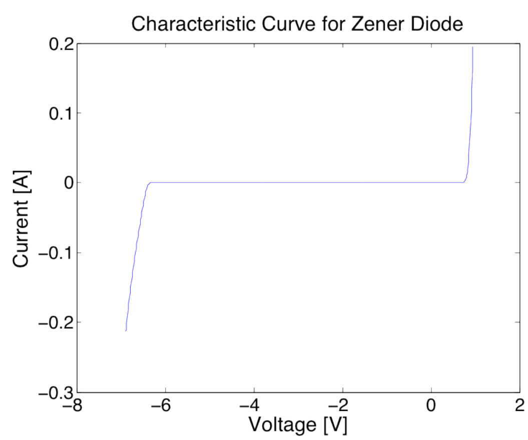

Figure 28

We know that the current through the diode can be modeled by

$$i_D = i_{sat} e^{V_{coeff} V_D} \tag{6}$$

where V_D is the voltage across the diode.
In addition, by Ohm's Law the current across the resistor is

$$i_R = \frac{V_0 - V_D}{R} \tag{7}$$

where $V_0 = 12V$ is the source voltage
Since the diode and resistor are in series $i_R = i_D$, and therefore

$$R = \frac{V_0 - V_D}{i_{sat}} e^{-(V_{coeff})(V_D)} \tag{8}$$

Since we want the voltage across the diode to be $6.2V$ and i_{sat} and the voltage coefficient were measured to be $1.36 \times 10^{-7} A$ and 25.46 respectively, then we can estimate the resistor value to be approximately 152.5Ω. Experimentally, we measured the resistor value to be approximately 220Ω. Note that the reasonable discrepancy between these values can be attributed to the fact that since the characteristic curve is exponential, small changes in the voltage coefficient will lead to very different resistor values. We determined that 680Ω was the smallest load resistor value which would not significantly decrease the circuit output voltage (where we defined "significant decrease" to be a decrease of at least 1%).
3.19 : Using Multsim, we simulated the circuit shown in Figure 29.

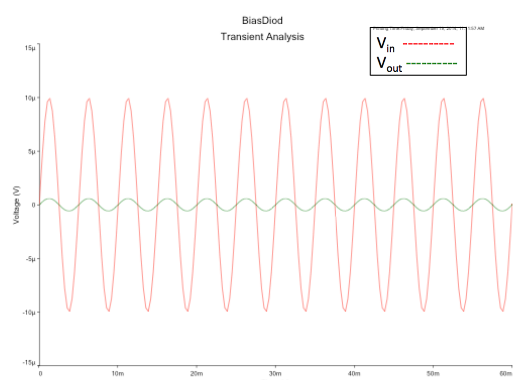

Figure 29

With an input AC voltage of amplitude 0.00001 V, the input voltage and output voltage shown in Figure 29. are shown, with their corresponding Fourier decompositions shown in Figure 30 and Figure 31, respectively.

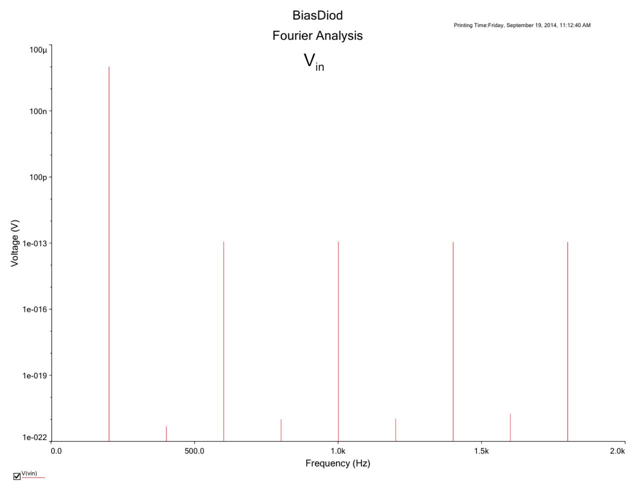

Figure 30

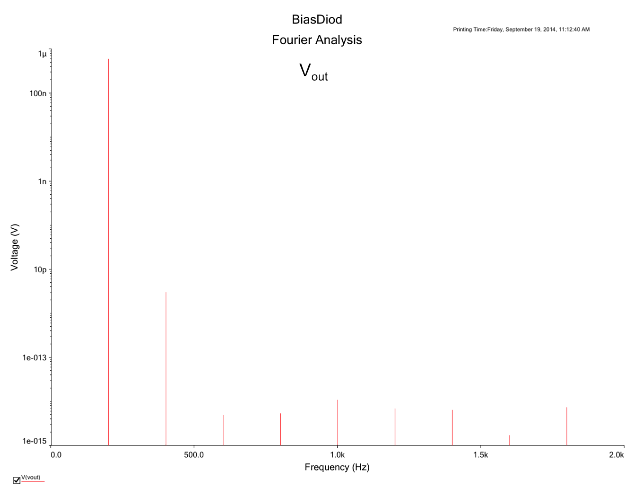

Figure 31

Since the signal is not greatly distorted by the circuited (shown in Figure , we would expect the output voltage to have a single peak, which corresponds to a sine wave. When the wave AC voltage is raised to 1 V, there is much greater distortion of the wave. It is clear from that this distortion from a perfect sine wave will contribute greatly to frequencies other than the first harmonic. Thus, the second harmonic will correspond to a higher voltage, and we will see significant frequency doubling (shown in Figure 33) for voltages of 0.3 V or higher.

3 Conclusion

In this lab, we studied the effect of diodes on the circuit. We applied graphical load analysis and perturbation analysis to determine resulting voltages and currents. From our results, it

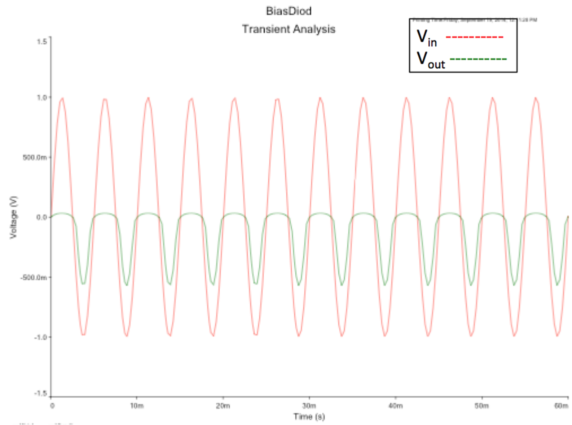

Figure 32

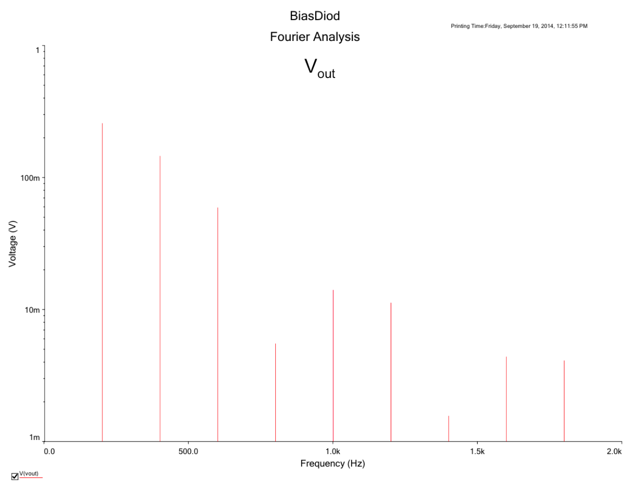

Figure 33

is clear that these are fairly powerful and precise techniques for determining the resulting voltages and currents of the circuits. Utilizing the diode, we were able to rectify signals, a result which is much more difficult, if not impossible to achieve with linear circuit elements. This understanding of diodes will be very important when we study transistors in future labs.