Grading Rubric Per Question:

- 100% if all aspects of approach and answer are generally correct
- 50% if earnest attempt, but major conceptual error, wrong approach, or illegible
- 0% if no attempt

Goals:

1. Learn how to perform automated IV data acquisition with dual SMUs.
2. Develop diode models for both large signal and small signal environments
3. Obtain diode model parameters from measured data.
4. Examine a simple diode circuit with small signal and large signal AC stimulus.
5. Examine harmonic generation from a non-linear circuit (exponential amplifier) using the FFT feature on the oscilloscope.
6. Examine the current and voltage characteristics of a filtered half-wave rectifier.

Preparation:

- Carefully review this document.
- Be sure to understand the analysis of the circuits to be built – they are covered in the HW1 problems.
- Examine the lab bench. There are 2 SMUs per bench - the upper instrument is at address 5 and the lower instrument is at address 7.
- Go over the diode data sheet available online. We will be using a silicon pn junction diode designated by 1N914A.
- Go over the op amp data sheets available online. We will be using LF353.

1.1 Diode IV Curves

- Build the diode test circuit. Place a 1N914A diode on a protoboard. Connect the Keithley 2400 SMU to the diode, connecting the SMU red lead to the diode anode, and the SMU black lead to the diode cathode. (The cathode end has the dark band.)
- Run the Keithley software for controlling the SMUs. (Start -> All Programs -> Keithley Instruments -> Labtracer 2.0.) A window should appear as shown below in Figure 1. If you have two SMUs on the screen, you will need to click the "delete" button to remove one.

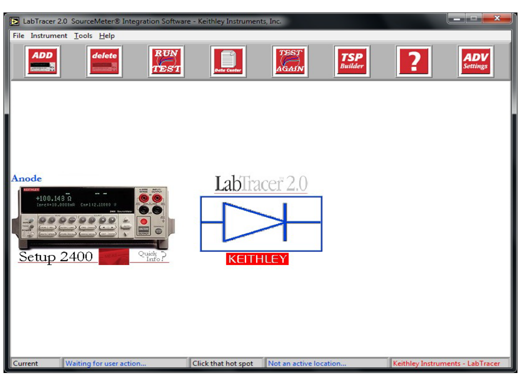

Figure 1. LabTracer main window with single SMU.

Note: By default, this software loads the measurement instructions that were last used by the program, so you probably will need to update the settings.

- Be sure that the 2400 instrument is displayed, not some other model. If it is some other model, click on the instrument image to change it to the 2400 SMU.
- Select Setup 2400 found under the image of the instrument. A series of tabs can be selected to set measurement parameters. The appearance of the window with the Source tab selected is shown below in Figure 2.

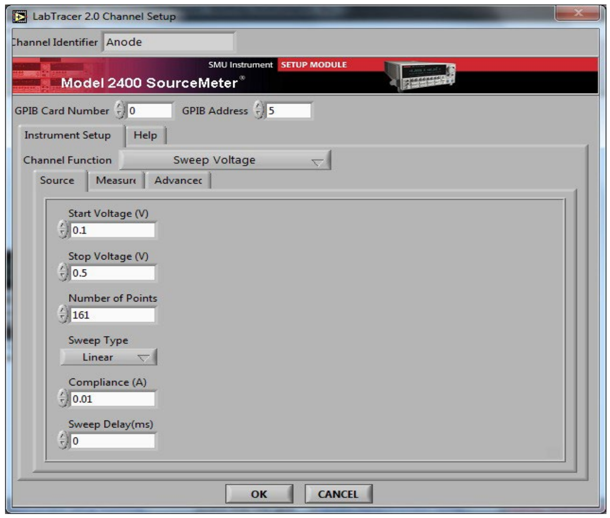

Figure 2. LabTracer Setup window with Source tab selected.

- Verify that the instrument GPIB address (upper center portion of the window) is set to 5. If it does not read 5, set it to 5.
- Setup your test with the following configuration:
  - Top SMU (GPIB address: 5) – driving the Base
    - Channel Function: Sweep Voltage
    - Source tab:
      - Start Voltage: 0.1 V
      - Stop Voltage: 0.5 V
      - Number of Points: 101
      - Linear sweep
      - Compliance: 0.01 A

(Note that we are sweeping the diode bias voltage over a small forward bias range.)

- Measure tab:
  - Check the box for Readback Voltage = Diode Voltage
  - Check the box for Measure Current = Diode Current
  - Integration (NPLCs) = 1

1.2 Diode IV Measurements and Data Acquisition

- Make sure the SMU is powered on.
- Strike the RUN TEST button on the Keithley LabTracer page and the measurement begins.
- When completed the DataCenter window appears as shown below in Figure 3. If no plot

appears, click on the Define Graph button and select voltage for the horizontal axis and current for the vertical axis. Get help from a TA if the data is not similar to what is shown in Figure 3.

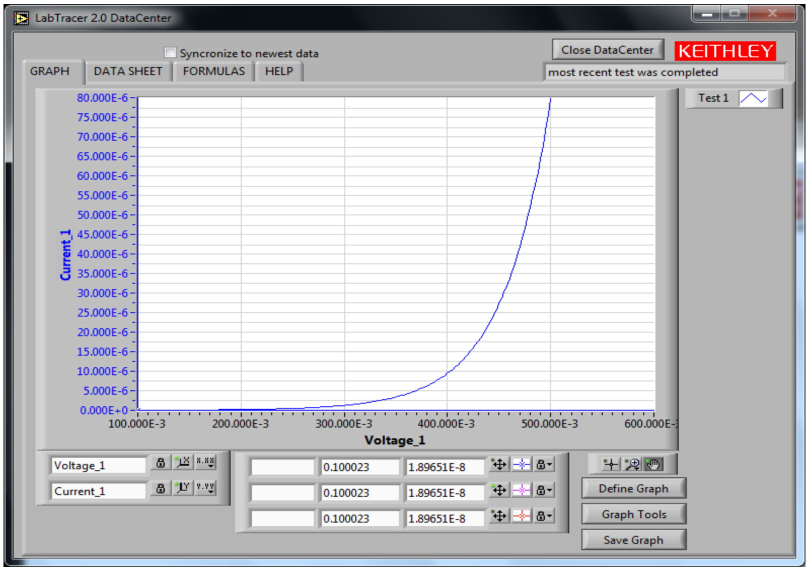

Figure 3. LabTracer DataCenter Graph of Diode IV curve. **Note:** this is not usable data. It is only shown as an example of what your data should look like.

- Click on the DATA SHEET tab and the measured data appears. *Striking the Save Data tab (lower right hand corner) will create a data file (ASCII) which you will store (on your memory stick) for later use.* This file will be used in the lab analysis.
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2.1 Large Signal Operation

- Build the diode test circuit shown below in Figure 4. Use +/- 12 V for the op amp's supply voltages. This is an exponential amplifier as you hopefully demonstrated in the homework. Record the measured resistor (R_2) value using the DMM.
- Connect a BNC tee at the output of the function generator and add the 50 Ω load termination at one end and the cable to your circuit on the other so that they are in parallel.

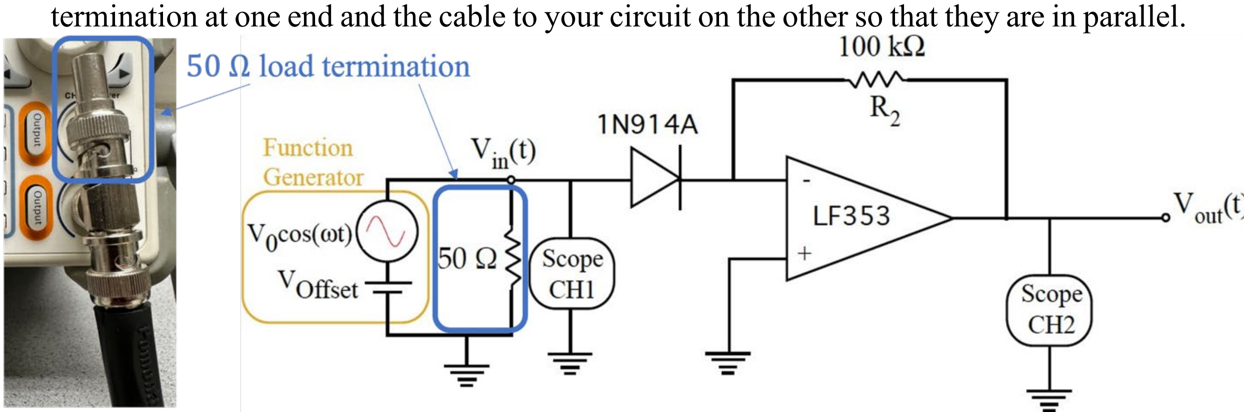


Figure 4. Diode test circuit for exploring large and small signal operation.

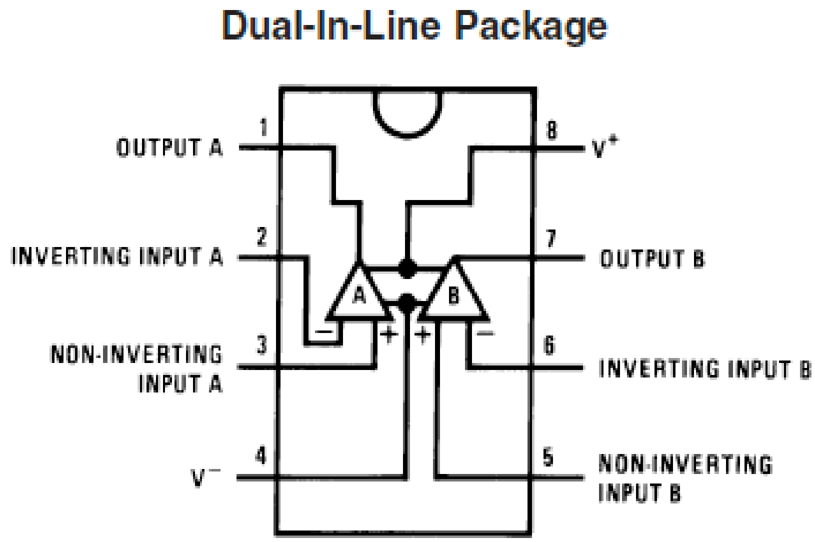


Figure 5. LF353 pinout diagram.

- You will use the function generator to provide both an AC signal and a DC offset voltage. Set the CH1 source impedance as 50 Ω (Utility -> CH1 -> HighZ/Load; choose Load) and turn on external triggering (Utility -> SyncON/SyncOff; choose SyncOn). Alternatively, you can recall ECE2100 setup so that the signal for the scope's external trigger is enabled and the 50 Ω load is selected.
- Set function generator settings to generate a Sine wave with frequency 250 Hz, signal amplitude 200 mV peak-to-peak, and offset voltage 300 mV.
- Set up the oscilloscope so the input and output waveforms are visible on the screen. Both channels should be on DC coupling, and each zero-voltage position (with its associated color marker on the left hand side of the display) should be on the vertical center of the display. (If the scope is on AC coupling, change it to DC by pressing the button with the channel number and then pressing the grey button next to Coupling to toggle it between AC and DC.) Since this is a 250 Hz input signal (with a corresponding 4 msec period), select 1 msec/div for the horizontal time base. Ask a TA for help if you don't know how to set this up.
- Adjust the scope channel gains so that a complete display of both the output and in input signals appear on the screen, with enough gain to see the waveforms. From these measurements, confirm the input signal has a 300 mV DC offset and a 200 mV peak-to-peak sinusoidal amplitude. It often helps to enable the data averaging feature by depressing the Acquire button, selecting Average from the menu, and setting the averaging to anything between 4 and 128. Choose just enough averaging to smooth the signal. Too much averaging adds a lot of delay in the time response to changes. For instance, if you change the vertical gain setting, it takes a while for the new signal to settle. To turn off averaging, you can select the Sample button from the menu.
- The output of the exponential amplifier should be a strongly distorted version of the input sinewave.

2.2 Large Signal Waveform Acquisition from Oscilloscope

- Waveform acquisition is performed by running the Tek OpenChoice Desktop Program from Tektronix found on the Desktop. A window should appear similar to Figure 6.

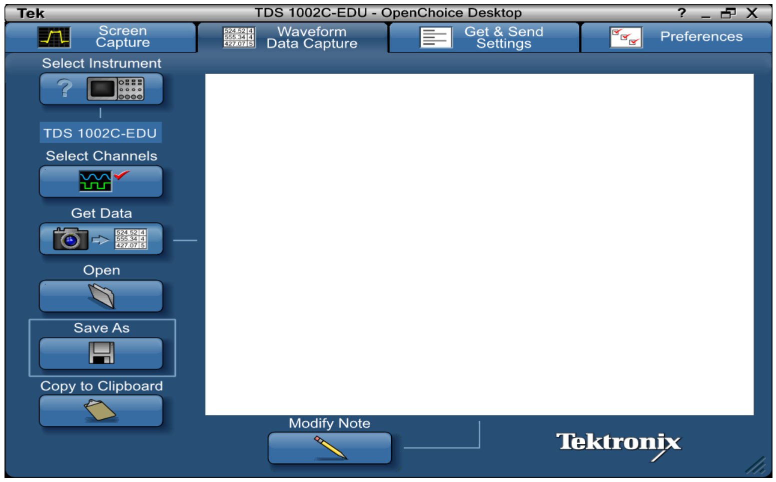


Figure 6. Tek Open Choice Desktop main window.

- Click the Select Instrument button and choose the USB0:xxx interface. Select the Waveform Data Capture tab, then click the Select Channels button and check both Channel 1 and Channel 2. Finally, click the Get Data button. After a few seconds, the waveforms should appear on the window. If not, get help from a TA before proceeding.
- *Save a screenshot of the waveform data by selecting the Screen Capture tab and saving from here, then placing the data file on your memory stick.*

2.3 Large Signal FFT Display and Acquisition from Oscilloscope

- The exponential amplifier is not a linear circuit. Nonlinear circuits can display frequency mixing between two input signals and harmonic generation of single inputs. We will look at the frequency spectrum of the input and output of the amplifier to observe this harmonic generation.
- To observe the frequency spectrum, we will use the FFT option on the scope. FFT stands for Fast Fourier Transform; and converts the time domain signal int a frequency domain signal.
- To display the FFT, press the red Math button on the scope. Be sure the waveforms are displayed prior to selecting the Math mode. To the right of the screen, a menu will appear. Scroll through the operations until you get to FFT and select that. Leave the scope's signal averaging in place. You can select which channel (channel 1 or channel 2) is to be used for the FFT calculation.
    - The best amplitude resolution occurs when we choose Flattop.
    - Using the Horizontal Scale (i.e., time base) rotary knob, set the horizontal scale to be 250 Hz/div.
    - Using the Vertical Scale rotary knob, set the vertical scale to be 10 dBs/div.
- Start by viewing Channel 1 (the sinusoidal input signal). Since the signal is a pure sine wave, the fundamental frequency component should be visible as a sharp peak at 250 Hz. Confirm that there is a signal at 250 Hz, as expected, and no other peaks in the spectrum.
- Now, switch to Channel 2 (the distorted output signal). You should see sharp peaks every 250 Hz from the fundamental (250 Hz) up to the 4^{th} or 5^{th} harmonic out beyond 1.25 kHz.

- Return to the computer and the Tek Open Choice Desktop program. With either channel's FFT displayed on the scope, click on the Select Channels button and check the Math box. Next, with the Waveform Data Capture tab selected, click the Get Data button and wait a few seconds for the FFT to appear on the Program's window. *Save the waveform data by clicking the Save As button and placing the data file in your memory stick. Save a separate data file for each channel.* The data is in the form of frequency (in Hz) followed by relative amplitude (in decibels).

3.1 Half-wave Rectifier

- The largest application for diodes is rectification, for use in AC to DC power conversion. Keep your op amp circuit from the previous step (you'll need it later) and on a different part of the protoboard, build the circuit shown in Figure 7. Do not include any capacitor in the circuit initially. *Measure and record the value of both resistors.*

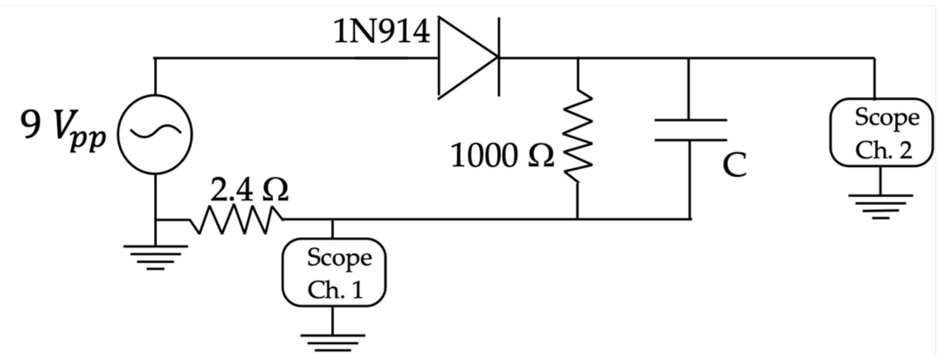


Figure 7. Half-wave rectifier circuit.

- Set the signal generator to operate at 60 Hz, with a 9 Vpp output. Remove the 50 Ω load that is connected to the BNC tee. The 2.4 Ω resistor is used as a current sensor. It will cause a slight voltage drop and thus error in our measured output, but the impact is very small and we will neglect its effect. (Commercial current-source power supplies use $R = 0.2\ \Omega$ or less for current sensing, but our oscilloscopes are not sensitive enough to see such a small signal.) Trigger on Channel 2. Please set the DC offset voltage to zero to get 9V peak-to-peak.
- Observe the input and output signals on the scope. You should see a half-wave rectified sine wave on Channel 2, and a very weak (~20 mV) half wave on Channel 1, which measures the current flowing through the diode. Set the signal averaging to 4. *Capture the screenshot AND data for the rectified signal using the Tek Open Choice Desktop program.*
- Retrieve a 33 μF capacitor. *Measure and record its value in your notes.*
- Connect a 33 μF capacitor to the circuit, as shown in Figure 7. The capacitor is electrolytic, meaning it has a polarity. Make sure you connect the positive lead of the capacitor to the diode and the negative lead of the capacitor to the 2.4 Ω resistor. Adjust the trigger voltage (small knob on the right side of the scope) to retrigger the signal, if needed. You should see a curve similar to what is shown in Figure 8. *Capture the screenshot AND data for both Channel 1 and Channel 2 using the Tek Open Choice Desktop program.*

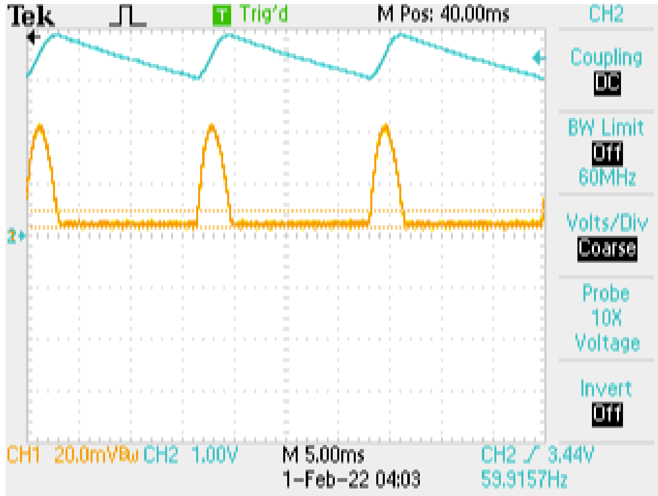


Figure 8. Half-wave rectified signal and ripple voltage.

- Put back the 50 Ω load on the output T of the signal generator.

4.1 Signal Demodulation with a Detector

- Using the op amp already on your board from part 2 of this lab, build an envelope detector for an amplitude modulated signal. This should be similar to the one you designed in the homework. A typical circuit will look like Figure 9. Choose a capacitor that will allow you to filter out a 1.8 MHz carrier wave but keep the voice signal (20 Hz to 20 kHz range). Recall that for an RC-filter, the cut-off frequency is given by:

$$f_c = \frac{1}{2\pi RC}$$

- *Measure and record the values of the resistors and the capacitor.*

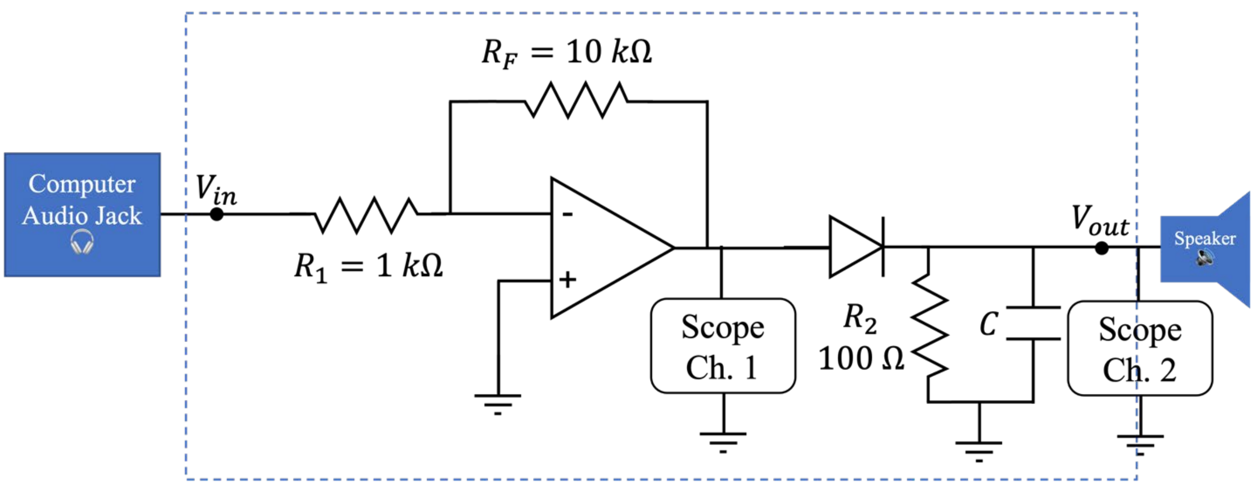
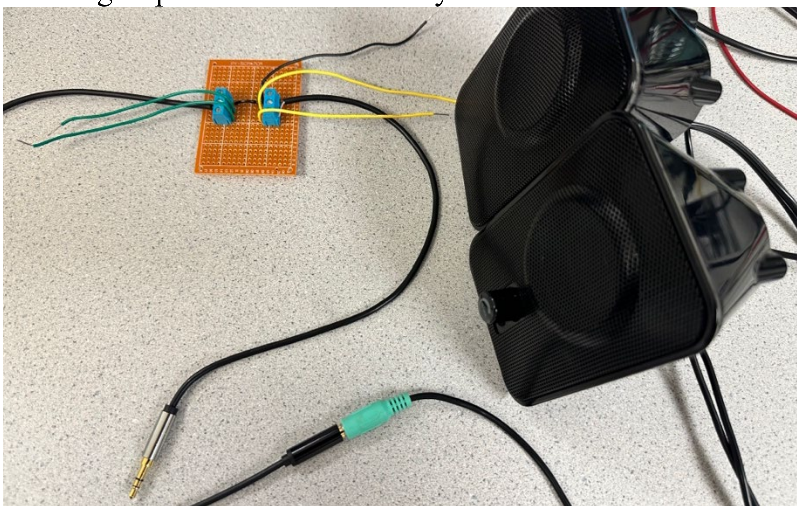


Figure 9. Half-wave signal demodulator and speaker connection.

- Log onto Canvas and pull up the audio file for this lab.

- Ask a TA to bring a speaker and testbed to your bench.



  - Note to the TA:
    - Make sure to turn the computer volume up!
    - Connect the audio jack to the computer and **both** of the wires from its testbed connection to the students' input node at V_{in}.
    - Connect the GND rail of the testbed board to the students' protoboard GND rail.
    - Connect **both** of the wires corresponding to the speaker side of the testbed to the students' output node at V_{out}.
    - Plug the speaker into a power source nearby (either USB or power outlet) and turn on the speaker.
- Press play on the computer and listen to the message. Can you understand it? *Write down what you hear.*
- Using the Run/Stop button on the scope, capture a representative image illustrating both the original signal on Channel 1 and the "demodulated" signal on Channel 2. *Capture a screenshot of this image using the Tek Open Choice Desktop program.*

Wind Down:
Dismantle your circuit and place your protoboard and the devices you tested back in their correct bins. Transfer all generated files to a USB or to your email so that you can access them outside the lab.

Analysis:
A.1 Diode IV Curve – Nonlinear Large Signal Model – Plot the diode IV behavior and fit it to the theoretical equation.

$$I_D = I_s\left[\exp\left(\frac{qV_D}{\eta k_b T}\right) - 1\right] = I_s\left[\exp\left(\frac{V_D}{0.026\eta}\right) - 1\right]$$

Where I_s is the reverse saturation fit and η is the ideality factor. You will need to tweak these two values to get the proper fit.

What you need to submit:

- Plot 1: Plot diode current in linear scale versus diode voltage in linear scale. On the same graph, also plot your calculated fit for the current using the theoretical equation. Note your values for I_s and η. Make sure the two curves are visible!

- Plot 2: Change the y-axis scaling of plot 1 to give the diode current in log scale and provide this graph as well. It may be easier to fit the curve in this format. Note: the relationship should appear linear in this view.

A.2 Small Signal Measurements – Diode Dynamic Resistance (r_d) – Using the same data as in A.1, for the 1N914A diode, prepare a graph of the small signal, a.k.a. dynamic resistance, of the diode ($r_d = \frac{dV}{dI}$) versus forward bias voltage. This is done by taking the difference quotient of the measured voltage to measured current. Put the y-axis in log scale. What is the measured dynamic resistance when $V_{DC} = 0.3\ V$? Using the diode exponential current equation, derive an equation for the diode's dynamic resistance as a function of diode current. Assume the forward bias is strong enough to neglect the $-I_s$ term. In other words, assume:

$$I_D \approx I_s \exp\left(\frac{qV_D}{\eta k_b T}\right)$$

Use the values you determined for I_s and η from question A.1 to estimate the expected dynamic resistance when $V_{DC} = 0.3\ V$.

What you need to submit:

- Plot 3: Plot of the dynamic resistance (with y-axis in log scale) versus diode voltage.
- Value of dynamic resistance from measured data when $V_{DC} = 0.3\ V$.
- Expression for dynamic resistance in terms of diode current.
- Value of dynamic resistance from derived expression when $V_{DC} = 0.3\ V$.

A.3 Large Signal Exponential Measurements – the exponential amplifier showed an output signal that is inverted relative to the input signal and stretched out. Why does this make sense?

- Your measured value for R_2.
- Plot 4: Plot the input and output signals for the exponential amplifier.
- Explain why you can tell the output signal (Channel 2) is an exponential function of the input signal (Channel 1).

A.4 Frequency Spectrum (FFT) – The frequency spectrum is presented as relative signal amplitude in decibels versus linear frequency. Subtract a uniform offset in decibels from the amplitude data of the output signal (Channel 2) at each frequency such that the amplitude of the fundamental is at zero decibels. Adjust your measured amplitude data of the input signal (Channel 1) such that the noise floor of each input and output signal is the same (at roughly -60 dB).

What you need to submit:

- Plot 5: Plot the input and output signals' frequency spectra on one set of axes for the range of frequencies from 0 to 1500 Hz.

A.5 Harmonic Generation for a Nonlinear Circuit – A Maclaurin series expansion of an exponential function is given as

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2} + \frac{x^3}{6} + \cdots$$

Assuming we approximate the diode current as $I_D \approx I_s \exp\left(\frac{qV_D}{\eta k_b T}\right)$, we can derive a Maclaurin series for it as such:

$$I_D \approx I_s \left[1 + \left(\frac{qV_D}{\eta k_b T}\right) + \frac{1}{2}\left(\frac{qV_D}{\eta k_b T}\right)^2 + \frac{1}{6}\left(\frac{qV_D}{\eta k_b T}\right)^3 + \cdots\right]$$

Using the trigonometric identity $cos(x)cos(y) = \frac{1}{2}[\cos(x+y) + \cos(x-y)]$, derive expressions for the coefficients of the first, second, and third harmonics of the diode current, assuming $V_D = A\cos(\omega t)$. Qualitatively explain why you see the trend you see in the amplitudes of the first three harmonics (250 Hz, 500 Hz, and 750 Hz) shown in the FFT of the exponential amplifier.

What you need to submit:

- Derivation for the first, second, and third harmonic coefficients.
- Explanation for the trend in the amplitudes.

A.6 Half-wave Rectification – Using the equation for voltage ripple, predict the expected voltage drop between charging cycles in a half-wave rectifier and correlate your predictions to the observed voltage drops measured with the capacitor.

$$V_R \approx \frac{V_p - V_{D,on}}{R_L C f_{in}}$$

What you need to submit:

- The measured values of the two resistors and the capacitor you used.
- Plot 6: Include the screenshot of the original rectified signal when no capacitor was in place.
- Plot 7: Include the screenshot of the signals when the 33 μF capacitor was in place.
- Calculated the ripple voltage you expect using the equation above and compare it with the measured data. State the diode turn on voltage $V_{D,on}$ you chose to use based on your graph in A.1.
- Explain why the current (Channel 1) has the time-domain shape that it displays.
- Explain why the capacitor does not charge to the full applied voltage. (Hint: the signal generator has an output impedance that is greater than zero.)

A.7 Detection – Plot the input amplitude modulated (AM) waveform (carrier + signal) and the output demodulated waveform detected on the scope for the circuit in Figure 9.

What you need to submit:

- The measured values of the resistors and the capacitor you used in your original circuit (Figure 9).
- Plot 8: Include the screenshot of the signals when your circuit from Figure 9 was in place.

- Could you hear the message clearly with the circuit? What are some possible reasons for the voice message/sound not being perfectly clean?
- What was the message you heard from the modulated signal?

A.8 Societal Impact and Ethical Debate – Given the right key and knowledge of the encryption method, anyone can decode a hidden message (as you did in this lab). This poses a problem for tech companies who want to encrypt user data and ensure the user's privacy. However, the Department of Justice continues to debate the idea of whether there should be such a thing as "warrant-proof encryption," through which tech companies so securely encrypt user data such that even law enforcement cannot intercept it. At the moment, tech companies are not required to provide law enforcement with a sure way to break the encryption. While this has the advantage of user privacy, it has the disadvantage of potentially impeding law enforcement from protecting citizens. What is your stance on this? What do you think should be done?

What you need to submit:

- Should companies be required to share their encryption methods with law enforcement? Explain why or why not.