



## Lab 8: Testing the Transmitter-Receiver System

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### 1. Purpose

The purpose of this exercise is test the subcircuits of the transmitter and receiver and to test the combined transmitter and receiver (up to the non-inverting amplifier).

#### 1.1 Equipment

- Agilent E3631A DC Power Supply
- Agilent 54600B Oscilloscope or Agilent 54622A Deep Memory Oscilloscope
- Agilent 33120A Function Generator
- Agilent 34401A Digital Multimeter

### 2. Review of the Transmitter-Receiver System

In Lab 7 you constructed the transmitter and receiver circuits (up to the non-inverting amplifier) including the transmit and receive coils as shown in Figure 1.

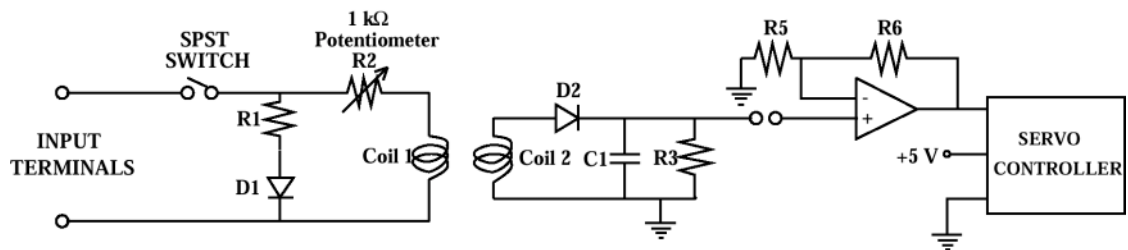


Figure 1: Transmitter and Receiver Circuit

The whole system will be integrated in Lab 9. In this lab you will test the sub-circuits of both the transmitter and receiver, as well as the composite system from system input to the output of the rectifier. The system (up to the non-inverting amplifier, with no connection between the receiver and the non-inverting amp) will operate as follows. The function generator will supply a high frequency sinusoidal signal at the input to the transmitter. When the SPST switch is closed, current will flow through the LED as well as the transmitting coil through the 1 kΩ potentiometer. The LED will be illuminated and its intensity will indicate the relative signal strength of the function generator. The 1 kΩ potentiometer will be used to adjust the strength of the signal applied to the transmitting coil. The current through the transmitting coil will induce a voltage across the receiving coil according to Faraday's Law of mutual inductance. Since the transmitted signal is sinusoidal, the induced voltage across the receiver coil will also be sinusoidal at the same frequency as the transmitted sinusoid. As will be explained in the following section, a diode acts as a one-way valve allowing current to flow easily in one direction and strongly opposing current in the other direction. The silicon diode in the receiver will allow current to flow through it to the right but not to the left. The arrow head in the diode symbol indicates the **forward** direction. Current flows easily in the **forward** direction but not in the **reverse** direction. When the sinusoidal voltage across the receiver coil is positive, current will flow through the diode in its **forward** direction and charge the capacitor  $C_1$  at a rate dictated by the **time constant**  $\tau = C_1 R_3$ . When the sinusoidal voltage across the receiver coil is



negative, the diode will cease to conduct since the voltage across the receive coil is trying to force current in the **reverse** direction of the diode. Hence, when the voltage across the receiver coil is negative, no current flows through the diode, and the capacitor will discharge through R3 according to the **time constant**  $\tau = C_1 R_3$ . If the **time constant**  $\tau = C_1 R_3$  is significantly greater than the period of the sinusoidal voltage across the receiver coil, then the capacitor will not have time to discharge before the next positive half-cycle comes along and *tops off* its charge. The result is a conversion of an AC (sinusoidal) signal to a DC (constant) signal.

The DC signal level across the combination of  $C_1$  and  $R_3$  will be proportional to the transmitted signal strength provided that your transmit and receive coils do not move during transmission. The DC signal level produced in the receiver across the combination of  $C_1$  and  $R_3$  will be too low to drive the servo controller. However, you will design and build an op-amp non-inverting amplifier to obtain the needed voltage gain to drive the servo controller. Your goal, when the system is completed is for your circuit to be able to control the servo over as much of its range as possible while adjusting the 1 k $\Omega$  potentiometer in the transmitter.

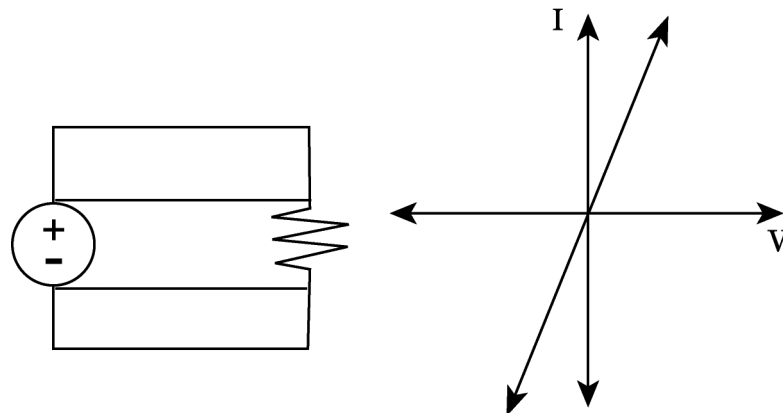
### 3. Diode Theory

The analysis of diode circuits is not part of EE61. However, some exposure to their behavior in the laboratory is appropriate. The following section is provided so that you have a basic theoretical explanation for the electrical behavior you will observe in both the transmitter and receiver circuits.

#### 3.1 Basic Diode Theory

Diodes are non-linear devices. This means that superposition does not apply to circuits containing diodes. When a voltage is applied across a resistor, current flows in proportion to the voltage where the proportionality factor is constant. The current-voltage (IV) characteristic for a resistor is shown in Figure 2, and is expressed analytically

by  $I = \frac{V}{R}$ . For a diode, the IV characteristic looks like Figure 3, and is



**Figure 2: Resistor circuit and its I-V characteristic**

described analytically by the formula  $I = I_s \left( e^{\frac{qV_D}{kT\eta}} - 1 \right)$ . Where  $I_s$  is the reverse saturation

current, the small ( $\approx 10^{-9}$ A) current that occurs in the negative voltage region.  $\frac{q}{KT}$  is a



temperature dependent constant  $\approx \frac{1}{0.026V}$  at room temperature.  $V_D$  is the voltage across the diode and  $\eta$  is a dimensionless constant determined by the composition of the diode (Silicon, Germanium, etc.)

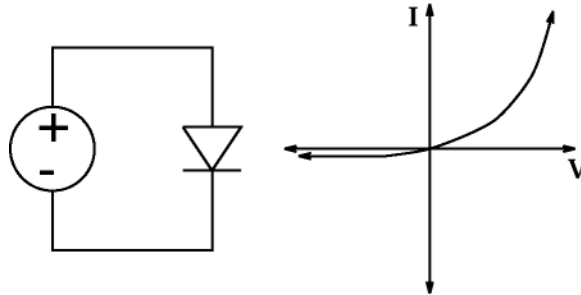


Figure 3: Diode circuit and its I-V characteristic

To observe the non-linearity of a diode, consider the circuit shown in Figure 4. When we apply  $V_1$  and  $V_2$  simultaneously, we find that the voltage across D is -3 V and the resulting current is very close to  $-I_s$ . If we attempt to use superposition, we find  $V_1$  produces 2 V across D and  $I_1 = 2190I_s$ .  $V_2$  produces -5 V across D and  $I_2 = -I_s$ . If we then sum these two currents, we would find  $I = 2189I_s$  which is obviously incorrect. Since the principle of superposition does not apply, a diode is a non-linear element.

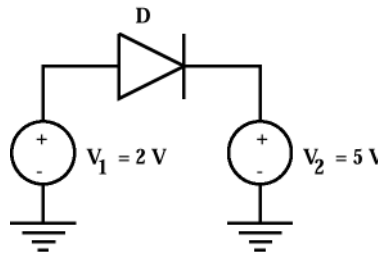


Figure 4: A diode circuit with 2 voltage sources.

### 3.2 Physical Diode Theory

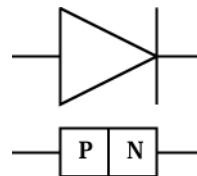


Figure 5: A diode symbol with associated P and N regions.

The next step in understanding diodes is to understand the physical principles behind the diode. A diode is composed of two regions of semiconductor (eg. silicon, germanium). A semiconductor is neither a good conductor such as copper, nor an insulator (dielectric) such as glass. A slab of semiconductor can be thought of as a resistor whose resistance depends on the amount of doping (impurities such as gallium or arsenic) that is implanted in the silicon. One region of semiconductor within the diode is called the **P** region. The **P** region has been doped with an impurity which causes the presence of **holes**, or incomplete covalent bonds in the semiconductor crystal. These **holes** in the **P** region attract electrons and therefore are analogous to positive charges. Hence, the **P** region may be thought of as being **Positive** (even though it is electrically neutral). The **N** region has been doped with an impurity which causes the presence of more electrons than are needed for the covalent bonds in the crystal. The



"extra" electrons (the ones not involved in covalent bonding) are available for conduction. The **N** region may be thought of as the **Negative** region due to the presence of the electrons available for conduction. At the junction between the two regions, a potential field is built-up. This field produces a barrier potential and is responsible for the (approx.) 0.7 V turn-on voltage (for silicon diodes) required in the **forward** direction to establish current flow. When a voltage is applied in the **reverse** direction we say that the diode is **reverse biased**. When the diode is **reverse biased**, the potential barrier builds up across the junction and opposes current flow through the diode. The greater the applied **reverse** voltage, the larger the barrier. When **reverse biased**, only a very small leakage current flows. This leakage current is called the **reverse saturation current** ( $I_s$ ).

### 4. Measuring the I-V Characteristic of a Diode

In order to observe the I-V characteristic of a diode, we need to be able to plot the current through the diode as a function of the voltage across the diode. The oscilloscope only measures voltages. However, it can plot one voltage as a function of another voltage. Consider the circuit shown in Figure 6. In this circuit,  $V_2 = V_R = IR$  and is therefore linearly proportional to I. When the LED conducts current in the **forward** direction, the voltage drop across it will be in the vicinity of 1.4-1.6 V. If the voltage across the diode is significantly greater than the voltage across the 10 Ω resistor, then  $V_1 \approx V_D$ . In order to observe the I-V characteristic, we will observe  $V_2$  as a function of  $V_1$ , with the understanding that the shape of the I-V characteristic is identical to the  $V_2V_1$  characteristic because  $V_2$  is proportional to I and  $V_1 \approx V_D$ .

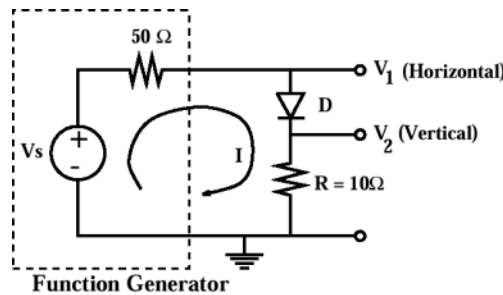


Figure 6: Diode circuit.

#### 4.1 Procedure for Measuring the I-V Characteristic of the LED

You will be examining the IV characteristics of the same type of Light Emitting Diode (LED) diode as you have in your transmitter circuit. Obtain another red LED from the parts bin.

1. Construct the circuit in Figure 6 on the bench-top breadboard. Set the function generator to produce a sinusoidal, 1 kHz, 4V (measured) peak-to-peak voltage  $V_1$ . Note that  $V_1$  is the voltage drop from the anode of the diode to ground.
2. Set your oscilloscope for X-Y measurements, and connect the X probe to  $V_1$  and the Y probe to  $V_2$ . To do this, press the Button labeled Main/Delayed. This will cause a softkey menu to appear. Press the softkey labeled XY. The probe connected to channel 1 provides the X axis and the probe connected to channel 2 provides the Y axis.
3. Sketch or print-out the I-V characteristic as it appears on the screen.
4. Return the resistor and LED to the proper drawers in the parts bin.



## 5. Testing the LED Indicator Circuit

In this section you will test the LED indicator circuit in your transmitter and determine if it operates close to the intended design from lab 5. The potentiometer is not to be connected in the transmitter circuit until later in the experiment.

1. Disconnect the SPST toggle switch from your breadboard. Connect the multimeter to the switch leads. With the multimeter set to measure resistance, toggle the switch and observe the resistance as you toggle the switch a few times. Put the switch in the "off" position. Reinstall the switch in your transmitter circuit.
2. Set the DC power supply to 0V and connect it to the input terminals of the transmitter. Increase the voltage to 5V and then toggle the switch to the "on" position.
3. You should see the LED glowing red. If the LED does not illuminate, remain calm. You can troubleshoot the circuit easily. Whether your LED illuminates or not, use the multimeter as a voltmeter and measure the voltage drops across the power supply, the switch, the current limiting resistor and the LED. Record all values measured. If your LED did not illuminate, try to figure out where the fault is. If the source voltage is correct (near 5V) and the voltage across the resistor is 0V, where is the 5V dropping? If the 5V is dropping across the LED, then it is **reverse biased**. Check the polarity of the power supply. If the polarity of the power supply is correct, then the polarity of the diode must be wrong. Remove the diode, invert the terminals, and reinsert it into your circuit. Once your diode circuit is operating, perform the voltage measurements again. Does KVL hold? Set the multimeter to measure current (ie. as an ammeter) and measure the current through the resistor and LED. Compare the measured current with its theoretical value as determined from Ohm's Law.
4. Toggle the switch to the "off" position. Disconnect the DC power supply from the transmitter input. Connect the function generator to the input of the transmitter. Set the function generator to produce a sinusoidal voltage at a frequency of 10 kHz. Toggle the switch to the "on" position. Adjust the amplitude of the function generator until a 10V peak-to-peak value is measured at the input of the transmitter.
5. The LED should be illuminated. Adjust the frequency to the range of 2-3 Hz. Observe the LED flashing. Increase the frequency until the LED appears to be emitting a continuous luminance. Record this frequency value. Reduce the amplitude of the function generator until the LED is barely visible. Measure the voltage (AC/RMS) across and current (AC/RMS) through the LED. How much power is the LED absorbing when it is barely emitting light?
6. Adjust the amplitude of the function generator to produce a 10V peak-to-peak voltage at the input of the transmitter. Use both channels of the scope to observe simultaneously the voltage across the resistor and the voltage across the diode. Explain why the waveforms are as shown on the scope.

## 6 Testing the Transmitter and Receiver

1. Obtain a 1 k $\Omega$  potentiometer and install it in your transmitter circuit.
2. Your coils should be wound such that the turns are near the notched end of the PVC. Each coil was wound either clockwise or counter-clockwise as seen from the notched end. Observe and record the relative orientation of the windings. That is, record whether the transmitter coil is wound clockwise or counter-clockwise as seen from the notched end. Repeat for the receiver coil. Orient your transmit and receive coils such that the magnetic flux produced in the transmitting coil will be maximally coupled to the receiver coil. To do this, place the notched ends of the coils as close to each other as possible with a common axis. You will find that it is necessary to keep the coils stationary during the measurements or the measurements will change with time causing frustration! You may



find it helpful to insert a pen or pencil through the two coils to stabilize them while you make your measurements.

3. Set the function generator to produce a sinusoidal voltage at a frequency of 10 kHz and a peak-to-peak value of 5V (as measured using the oscilloscope). Using both channels of the scope, measure the peak-to-peak voltage across both the transmit and receive coils. The autoscale utility of the oscilloscope may not work properly for the signal across the receive coil. Use the manual vertical (amplitude) adjustment on the scope to obtain an appropriate waveform on the scope. Adjust the potentiometer until the voltage across the transmit coil is maximum. Increase the frequency by a factor of ten and make another set of measurements. Each time you change the frequency, you will have to examine the voltage produced by the function generator and adjust its amplitude to maintain a peak-to-peak value of 5V. Continue until you have reached the frequency limit of the function generator. Comment on any unusual waveshapes observed.
4. The parallel RC circuit ( $C_1$  and  $R_3$ ) in the receiver has a time constant  $\tau = C_1 R_3$  as explained in the introduction of this lab exercise. This time constant determines both the rate that  $C_1$  will charge as well as the rate it will discharge. Considering the values of  $C_1$  and  $R_3$  you have on your board, what is the value of this time constant? Measure the voltage across  $C_1$  and  $R_3$  at a frequency of 200 kHz (using the scope) along with the voltage across the transmitter coil. You choose the amplitude. Slowly vary the amplitude of the transmitted signal by varying the potentiometer. Observe the transmitted signal strength and the DC value across  $C_1$  and  $R_3$  as you adjust the potentiometer over its entire range. Explain what you observe.

## 7. Questions to be Answered

1. Considering the range of DC values your receiver produced while varying the potentiometer in the transmitter, how much voltage amplification will you need to drive the servo controller? Will you be able to sweep the servo through its complete range? Explain.
2. Explain in your own words how the rectifier circuit in the receiver converts AC to DC.
3. Explain in your own words how a diode works.