Physics 3150, Laboratory 4
Diode Circuits

Feb. 15 and 17, 2016 (The Monday lab may be continued later due to a snow cancellation.)
Last revised Feb. 15, 2016, by Ed Eyler

Purpose:

1. To investigate practical circuits using diodes as one-way switches, including clamping circuits, rectification, and simple dc power supplies.
2. To construct a simple mixer, using diode nonlinearities to produce difference frequencies.

References:

Chapter 3 of Eggleston. Other descriptions include Chapter 3 of Kaplan and White, Chapter 1 of Horowitz and Hill, and Chapter 4 of Meyer.

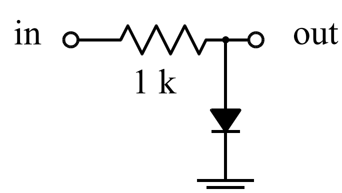
Equipment:

1. Two function generators (for frequency mixing).
2. Digital oscilloscope.
3. Breadboard with power supplies and hookup wire.
4. A selection of 1/4W or 1/2W resistors.
5. Transformer with a 6.3 to 20 Volt secondary at 60 Hz.
6. 1N914 or similar small-signal diodes (type 1N4148 is extremely similar).
7. 1N4003 or similar rectifier diodes.
8. Electrolytic capacitor, 10-50 μF.

I. Basic diode circuits.

A. ***Diode Clamps or Clippers***

Build the following circuit, variously called a diode "clipper" or "voltage clamp" by different authors:

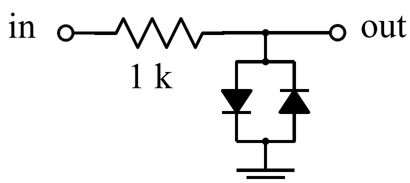


1) Drive this circuit with a 5 V, 1 kHz sine wave. Why is it called a clamp or clipper? At what voltage does it clip the ouput? How does it deviate from a perfect voltage limiter?
2) The deviation occurs because the diode isn't a simple switch that is either on or off. Instead there is a small exponential transition region. This gives rise to a concept called *dynamic resistance*. We normally define resistance as $R = V/I$. However, $V(I)$ for a diode is not linear, so we define dynamic resistance as $r = dV/dI$. In other words, it is defined in terms of differential quantities and applies to small ac signals. A purely exponential model for a silicon diode gives $r = (n)(26\text{ mV})/I_d$, where $n \sim 2$ is a device-dependent factor, 26 mV is the value of e/k_BT at room temperature, and I_d is the dc current through the diode.

To measure the dynamic resistance *r*, set the signal generator to a small value, for example 0.2 $V_{p\text{-}p}$. The 1k resistor and *r* will then act as a voltage divider. By measuring the output ac voltage (using ac coupling on the scope), you can determine *r*. Do this for several values of the dc offset of the signal generator. This will not change the ac voltage, but it *will* change the dc bias point of the diode and thus will change I_d. For each value of the dc offset, you will need to measure the average dc values of both the input and output voltages. The difference between these values gives the dc voltage drop across the 1k resistor, from which you can the current through the diode.

3) Finally, you can plot *r* as a function of $1/I_d$. According to the model above, the slope should be linear. What do you see? Compare the slope you measure in the linear region with the prediction for *r* in part (2).

A variation of this circuit is the bidirectional limiter, with another diode as shown:

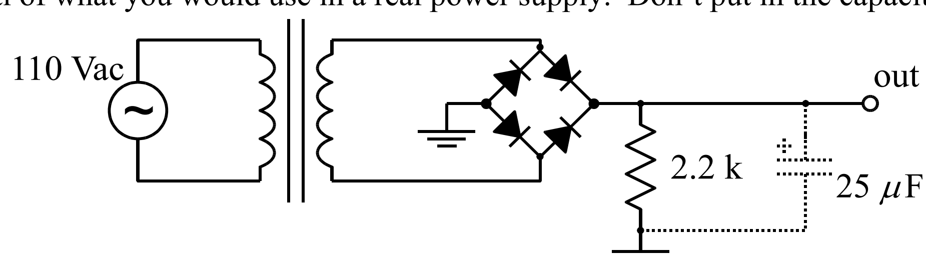


Build this modification of your circuit and try driving it with a 5 $V_{p\text{-}p}$ sine wave. Explain your observations. Why is the circuit called a limiter and what might you use it for?

B. *Full-wave rectifier and an unregulated dc power supply*

When two or more inductive windings are magnetically coupled to give a large *mutual inductance*, they can be used to form a transformer. In power applications, the transformer is most often used to alter the voltage of a power source without significant loss of energy. In high-frequency applications, it is frequently used to alter the characteristic impedance of a signal source.

Here we will use a simple step-down transformer to construct a rudimentary low-voltage power supply that operates from 117 V line power. Build the following circuit using using 1N4003 rectifier diodes. They can conduct a lot more current than 1N914 diodes. The 1N4003 is much more typical of what you would use in a real power supply. Don't put in the capacitor, yet.



Measure the ac output voltage of the transformer using a DMM set to ac Volts. DO NOT try to measure the voltages across the transformer by connecting the scope ground to one of the transformer coils – they are not at ground. However, the output is perfectly safe to measure. Sketch (or record) and explain the waveform that you see. Why is this the first step in building an ac powered dc power supply? What is not yet satisfactory about the output?

Now add a filter capacitor in the range 10-50 μF, paying close attention to the polarity! What affect does it have on the output? Is the remaining "ripple" on the output in reasonable agreement with the prediction of Eqs. (3.16) and (3.17) in Eggleston? Explain the average value of the output voltage that you observe, in terms of the transformer output voltage.

II. Diode Mixer

A. Principles

The nonlinearity of a diode can be put to explicit use when you need to create new frequencies that are sums, multiples, or differences of other frequencies present in a circuit. Here we will construct a diode mixer, whose input is two sine waves at frequencies ω_1 and ω_2 and whose output is a sinusoid at the difference frequency $\omega_1 - \omega_2$.

As we have already seen, the current through a diode is an exponential function of the voltage drop. For present purposes we can represent the forward-biased current adequately by a simple exponential,

$$I = A_1\left(e^{V/A_2} - 1\right),$$

where the constants A_1 and A_2 are determined by the device physics and temperature.

If we take a Taylor expansion, the response is displayed explicitly as a sum of linear and nonlinear terms,

$$I = A_1\left\{\frac{V}{A_2} + \frac{1}{2}\left(\frac{V}{A_2}\right)^2 + \cdots\right\} \tag{1}$$

Thus if the input is a sum of two sinusoids with different frequencies,

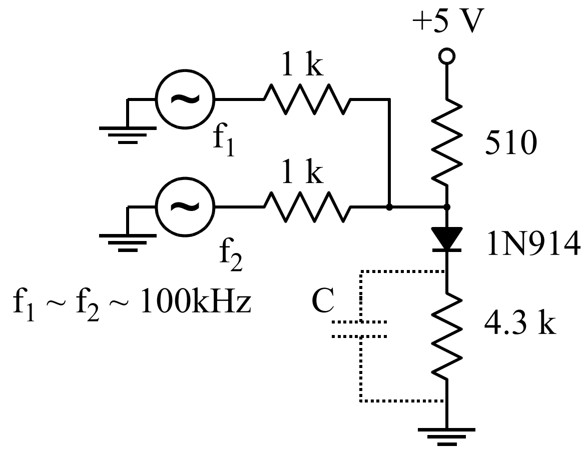
$$V = V_1 \cos\omega_1 t + V_2 \cos\omega_2 t, \tag{2}$$

the output will have components not only at frequencies ω_1 and ω_2, but also at dc (zero frequency) and at frequencies $2\omega_1$, $2\omega_2$, $\omega_1 - \omega_2$, and $\omega_1 + \omega_2$. If the cubic and higher order terms are included in Eq. 2, we will obtain even more new frequencies. The dc term corresponds to using the diode as a rectifier, as in the first part of this laboratory. This time, though, we will be looking specifically for the difference frequency, the "mixture" of the two inputs.

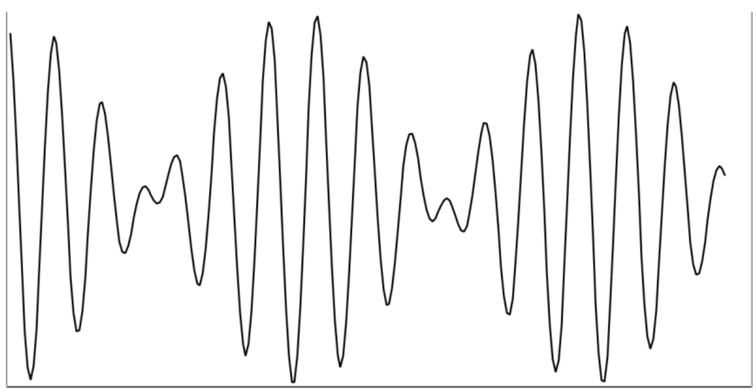
Mixers are used widely in rf technology, where an incoming signal at w_1 containing information is commonly combined with a stable "local oscillator" at w_2 to produce a difference frequency much lower than the input frequency, but still containing all of the information. This process is called "heterodyning," and is used in almost every radio receiver. It is also seen commonly in the physics laboratory, where the procedure is used not only at rf frequencies, but even for coherent optical radiation from lasers.

B. Procedure

Construct a basic mixer circuit as shown here, omitting the capacitor initially. The two signal generators are connected through 1K resistors so their outputs do not perturb one other. Despite this precaution, some signal generators do not perform acceptably, so make substitutions if necessary. The 510 Ω resistor from +5V to the diode is used to provide a bias voltage, so the diode is always slightly conducting even when no input signal is present. A direct connection can't be used because the signals would then be shorted to the power supply, which has a very low ac impedance. The 4.3K resistor is used both to limit the bias current and to sample the current through the diode.



Set the two signal generators to produce sine waves with similar frequencies somewhere near 100 kHz, separated by about 1-10 kHz. Using an oscilloscope with 10× probe, look at the top (anode) of the diode and set the amplitudes so that each signal generator substantially perturbs the dc level, but without actually reverse-biasing the diode (why?) Now look at the output voltage across the 4.3 K resistor (at the cathode of the diode). For small and equal input signals you should see a simple beat note, ideally something like this:



Increase the amplitude until the signal becomes slightly asymmetric due to the diode nonlinearity. It is only here that a strong mixing effect will be seen. Next, connect a capacitor across the 4.3 K resistor to form a low-pass filter, so you can see the difference frequency without the high-frequency oscillations. Choose the capacitance so that RC is slow compared to the 100 kHz inputs, but fast compared to the difference frequency (1-10 kHz). You may want to use ac coupling on the oscilloscope, so you can see the small signal without the dc level set by the bias current. Experiment until you get a clean sinusoidal difference frequency output.

C. Questions for Part II

1. Verify the discussion above by explicitly writing the response of the diode as a sum of sinusoids, finding the constants in the expression below. (Hint: it's probably easiest to write things using complex notation, then regroup the terms)

$$I = c_1(V_1^2 + V_2^2) + c_2(V_1 \cos\omega_1 t + V_2 \cos\omega_2 t)$$
$$+ c_3(V_1 V_2 \cos(\omega_1 - \omega_2)t + c_4(V_1 V_2 \cos(\omega_1 + \omega_2)t + c_5(V_1^2 \cos 2\omega_1 t + V_2^2 \cos 2\omega_2 t)$$
$$+ \text{ terms in higher orders of } V_1,\ V_2.$$

2. Why is the 5V bias voltage helpful in obtaining satisfactory operation without severe distortion?

3. Clearly explain why the beat note envelope disappears when a low-pass filter is added to the output, while the difference frequency from nonlinear mixing remains. They both appear to have the same frequency, so why don't both survive?