

EXPERIMENT XI
BUILD AND SIGNAL-TRACE AN AM RADIO CIRCUIT

If you have a set of headphones with a 1/8" stereo plug (the most common type), please bring it with you to Lab to listen to your AM radio.

Introduction.

Like the transistor amplifier lab (Lab 10), this Lab goes beyond the material that you learn in lecture and class. You will use your knowledge of electronic circuits to construct an AM radio and understand how it works.

The term “radio” includes both the broadcast and reception of an audio signal, whose frequencies are between about 100 and 10,000 Hz. An immediate difficulty is that direct broadcasting of electromagnetic waves of these relatively low frequencies is not very practical, in large part because antennas must be roughly one wavelength long to be efficient. *What is the wavelength of a 100 Hz electromagnetic wave?*

Usable broadcasting of electromagnetic waves involves frequencies of 0.5 MHz or higher. The challenge is to superimpose an audio-frequency signal on a “carrier” frequency $\omega_c = 2\pi f_c \geq 3 \text{ MHz}$. One way of accomplishing this is via *amplitude modulation*, the principle of AM radio broadcasting. In its simplest form, the audio frequency signal is multiplied by the carrier wave, $\cos(\omega_c t)$. For the case when the signal is a pure audio tone of angular frequency ω_A , the product of the two frequencies can be written as

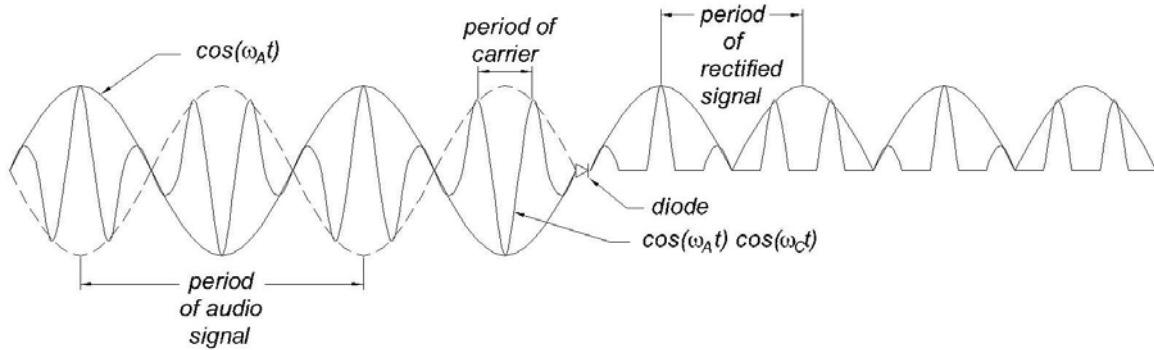
$$\cos(\omega_A t) \cos(\omega_c t) = \frac{1}{2} [\cos(\omega_c + \omega_A)t + \cos(\omega_c - \omega_A)t], \quad (1)$$

using a trig identity. Because the carrier frequency is much larger than the audio frequency ($\omega_c \gg \omega_A$), the result of the multiplication is a combination of two high-frequency signals. If we passed this waveform through a low-pass filter, say with characteristic angular frequency $2\omega_A$, nothing would emerge since the waveform contains only high frequencies. It is not sufficient for the radio receiver to amplify the signal – you cannot hear the high frequencies that it contains. Rather, the radio receiver must *demodulate* the AM signal, revealing the audio-frequency information that has been shifted to high frequency by the modulation.

Demodulation cannot be performed by linear circuit elements alone (*i.e.*, by resistors, capacitors, inductors in which oscillatory voltages and currents are related by a generalized Ohm’s law, $V = IZ$, or even by linear amplifiers in which $V_{\text{out}}/V_{\text{in}}$ is independent of frequency). These devices do not change the frequency of a signal, whereas an AM radio receiver must transform the high-frequency modulated signal in a low-frequency audio signal. A radio receiver must contain at least one nonlinear device. The simplest nonlinear circuit element is a diode, which

you have studied in Lab 10. And indeed, a basic AM radio can be made using a diode, although the way in which the diode demodulates the AM signal is quite sophisticated.

The lefthand side of the figure below shows a modulated signal, which has the form of eq. (1). The diode *rectifies* this waveform, meaning that it transmits only the positive portion of the wave, as shown on the right of the diode in the figure.

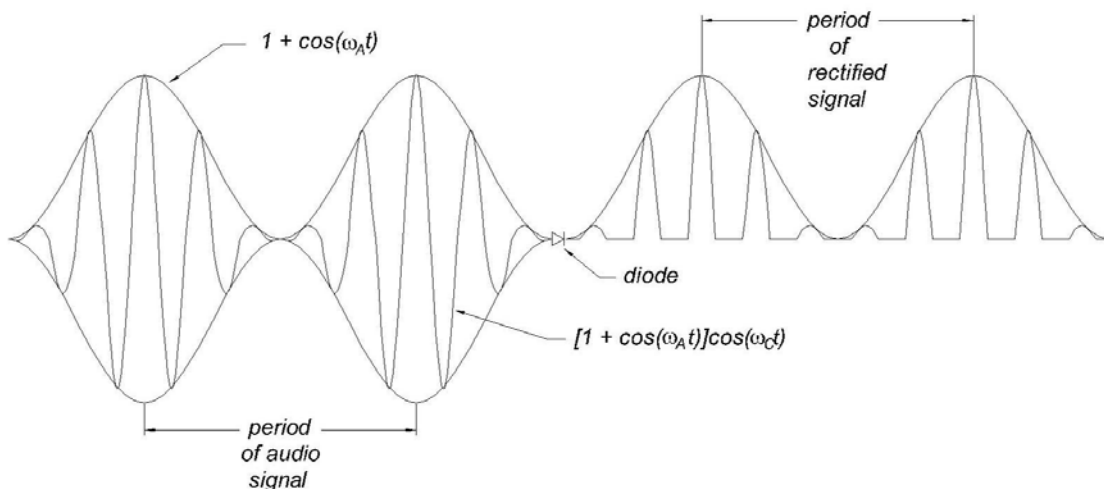


The rectified signal now has low-frequency content, as can be verified by passing it through a low-pass filter. *A hint that the waveform on the right in the figure above has low-frequency content, while the waveform on the left does not, is that the average of the waveform on the right is nonzero \Rightarrow there is a zero-frequency component.* However, the period of the rectified signal is one half the period of the period of the audio signal, and so the rectified signal has twice the desired frequency. If the signal were the voice of a person, the effect would be humorous at best.

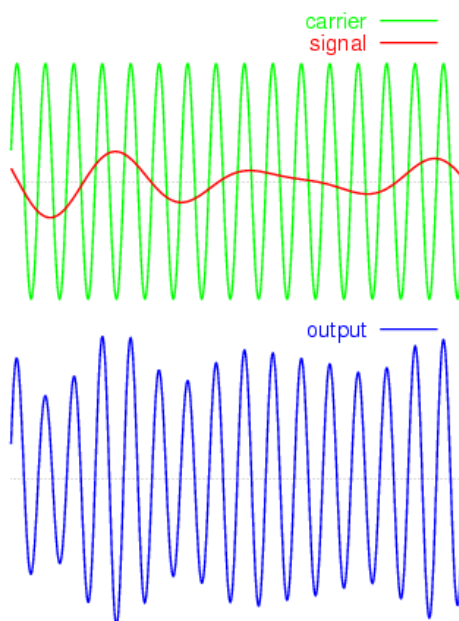
To be able to extract an audio signal of the proper frequency from the modulated wave, the modulation is performed by first adding an offset to the audio signal, and then multiplying it by the carrier wave. For the example of an audio signal of angular frequency ω_A , an appropriately modulated waveform is

$$[1 + \cos(\omega_A t)] \cos(\omega_C t) = \cos(\omega_C t) + \frac{1}{2} [\cos(\omega_C + \omega_A)t + \cos(\omega_C - \omega_A)t]. \quad (2)$$

This waveform and its diode rectification are shown in the figure below. Now the period of the rectified signal is the same as that of the audio signal, as desired.



An AM radio transmitter implements the scheme of eq. (2), as shown in the figure below. Since the modulation circuit results in a change of frequencies, it cannot be built using only linear circuit elements, but we do not pursue this further here.



The earliest form of radio transmission did not use amplitude modulation. Rather, the carrier wave was turned on and off at intervals corresponding to the “dashes” and “dots” of Morse Code; no voice signals were transmitted. AM radio came into use only around 1920, following the development of the diode vacuum tube. The commercial AM radio band is between 500 and 1600 kHz. Only 10 kHz is allotted to each radio station. Since the modulation requires use of frequencies both higher and lower than the carrier frequency, the maximum allowed audio frequency is only 5 kHz, which is too restrictive for high-quality sound reproduction. To overcome this limitation, new radio bands were created at higher frequencies and with larger bandwidth. And to provide better sound quality, another type of modulation, FM = frequency modulation, was developed for use with these new radio bands.

The rest of this Lab focuses on understanding of an AM radio receiver. The job of such a receiver is to

1. **Receive** the high frequency signal (often called the RF or *radio frequency* signal) with an antenna.
2. **Select** the desired carrier frequency (“tune” to the desired radio station).
3. **Detect** the signal using a diode to restore low-frequencies to the modulated RF signal.
4. **Amplify** the diode-rectified signal.
5. **Filter** out the audio frequency part of the rectified signal with a low-pass filter for clearer sound. (Steps 4 and 5 could be reversed.)

In previous Labs this semester you have built circuits that perform each of these functions separately. In this Lab you combine them to build a working AM radio. Besides listening to your radio, you will use an oscilloscope to examine the signal at each stage.

This Lab differs somewhat from previous Labs in that the emphasis is on making a device work, rather than on a program of measurements. This Lab is therefore the most representative of how experiments actually proceed, since in most cases much more effort is spent in making a new apparatus work than in taking data with that apparatus.

1. I Can't Believe That This is a Radio.

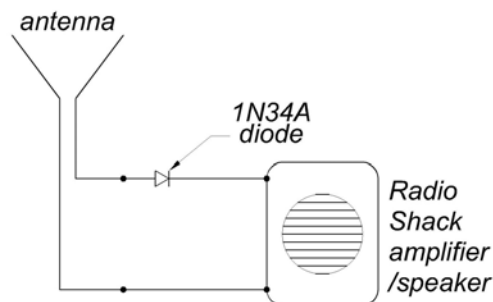
On your lab bench is a small Radio Shack amplifier/speaker with two wire leads. Connect these leads to the leads of the antenna (whose wires extend outside the lab). Turn on the amplifier via the thumbwheel, and you should hear a faint mixture of signals from several radio stations.

How can this be? The Radio Shack device is labeled “amplifier” not “radio”.

Indeed, if the Radio Shack amplifier were a high-quality linear amplifier it would not act like a radio. But this low-cost amplifier is rather nonlinear in its behavior, and a nonlinear circuit element is essential for a radio receiver. Hence, a poor amplifier can act as a radio receiver, and part of the “noise” of such an amplifier is pickup from radio stations.

2. Antenna + Diode

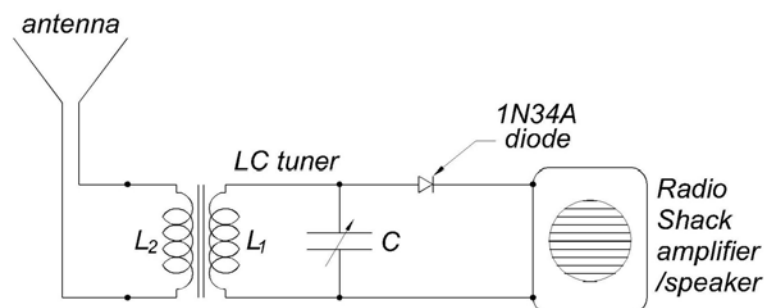
Connect the antenna leads to a circuit that contains a 1N34A germanium diode (with diode drop of only 0.2 V), as shown in the figure below. Build the circuit on a “breadboard”.



Is this a better or worse radio than that of part 1? Does the direction of the diode make any difference to the performance of this receiver?

3. Add a Tuner

To isolate the signal from a single radio station, your receiver should include a kind of “bandpass” filter that can be tuned to any desired central frequency. Among the basic circuits that you have studied, an LC resonant circuit is best suited for this task. Recall that the resonant angular frequency of an LC loop is $\omega_{\text{res}} = 1/\sqrt{LC}$ where L is the inductance and C is the capacitance of the circuit elements. We desire that $\omega_{\text{res}} \approx 10^7$ Hz to tune on AM radio stations.



Build a parallel-plate capacitor out of two brass bars, separated by a piece of index card. By sliding the upper bar with respect to the lower bar, you can vary the capacitance of your capacitor, which will provide the tuning of your receiver.

Use the solenoid with $N_1 \approx 100$ turns of fine wires as the inductor L_1 for your resonant circuit.

The problem now is how to couple the antenna to the resonant LC circuit. An elegant way to do this is to attach the antenna to the second inductor coil, which has $N_2 = 10$ turns and which slides over the first inductor to form a transformer. Then, you obtain an amplification of the voltage of the antenna signal according to the law of an ideal transformer (p. 6 of Lab 7),

$$V_2 = V_1 \frac{N_2}{N_1}, \quad (3)$$

when inductor i has N_i turns. Furthermore, a limited amount of tuning can be obtained by sliding one inductor with respect to the other. Try it.

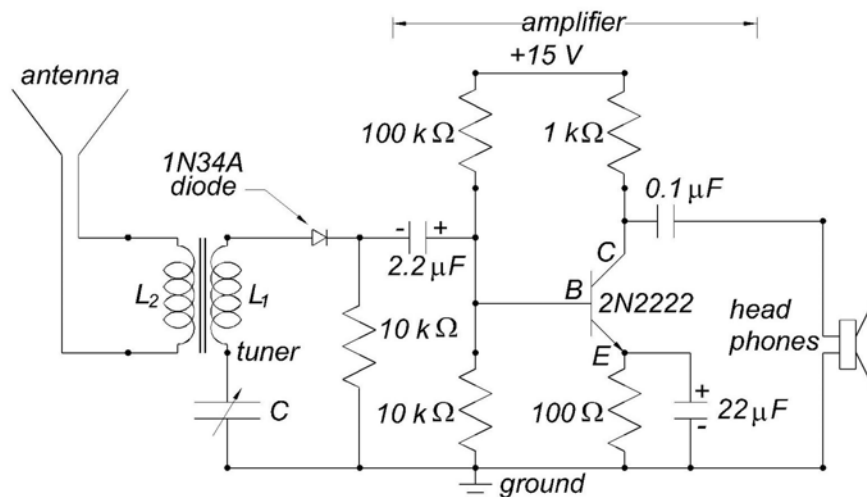
However, the primary tuner for your AM receiver is the capacitor. How many different radio stations can you detect by sliding one bar of the capacitor relative to the other?

To tune on one radio station while rejecting the signal from an adjacent channel would require a resonant circuit whose resonance curve has a full width at half maximum of only 10 kHz. The quality of the tuning circuit is a major factor in the overall quality of a radio.

4. Add Your Own Amplifier

Tune the radio of part 3 to the strongest station you can find, and replace the Radio Shack amplifier/speaker with your headphones, using the headphone jack with two leads. Probably you won't hear anything. The signal is too weak.

To be able to hear the radio signal on your headphones, build the version of a 2N2222 transistor voltage amplifier shown below, which attaches to the 10 k Ω load resistor that is placed across the diode.



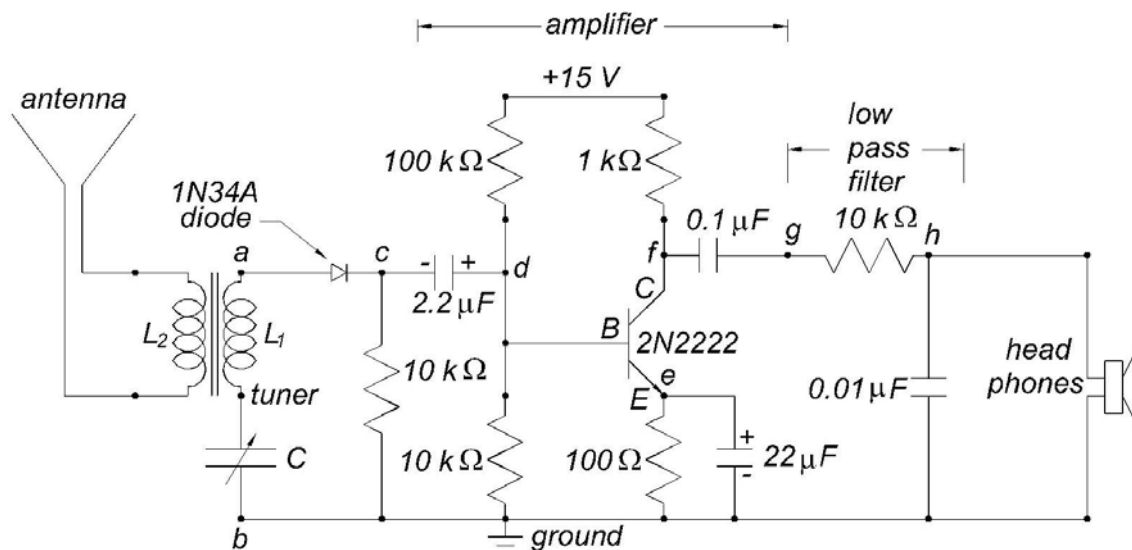
Do NOT connect the antenna to the ground of your amplifier circuit. Use the transformer!

This is the same circuit that you built in Lab 10, with only minor variations. The bias voltages for the transistor Base still involve a 10:1 voltage divider, but the resistor values have been multiplied by 10, which helps the diode to perform more like an ideal diode. Also, the $100\ \Omega$ resistor connected to the Emitter now has a $22\ \mu\text{F}$ capacitor in parallel, which improves the performance of the amplifier at high frequencies. If you have time, compare the performance of the circuit without the $22\ \mu\text{F}$ capacitor and with the Base bias resistors having values $1\ \text{k}\Omega$ and $10\ \text{k}\Omega$.

If you have constructed your amplifier correctly, you should be able to hear, somewhat faintly, the radio signal in your headphones now. If not, there may be a problem with the circuit, and you may wish to jump ahead to part 6 = circuit diagnostics with scope and wave generator.

5. Add a Low-Pass Filter

The performance of your circuit can be improved slightly by adding a simple RC low-pass filter, as shown in the figure below.



6. Circuit Diagnosis with a Wave Generator and Oscilloscope

It is almost impossible to build a circuit as complicated as the one above such that it works correctly on the first try. Rather, it is helpful to have a step-by-step set of checkout procedures to verify that one part of the circuit is working before constructing the next. Here we sketch a possibly useful set of tests of pieces of the circuit, which also may teach you a bit more about how those subcircuits work.

Your breadboard has the flexibility to accommodate most of these tests with minimal disruption to the wiring of the rest of the circuit.

6a. The Diode

Connect the output of the Wavetek generator to test points *a* and *b* shown on the lower figure on p.6, and use “tee” to send a copy of the output to Ch 1 of your oscilloscope. Set the output frequency to about 1 MHz to simulate a radio carrier wave, and set the amplitude to about 1 V so that you will have no trouble seeing the effect of the signal.

Connect the 10X scope probe to Ch 2 of the scope, connect the probe tip to test point *c*, and connect the probe ground to test point *b* (where the probe ground should remain for all subsequent tests). The scope display of Ch 2 should be a clipped off version of the input signal on Ch 1. If not, there is trouble with your diode. The clipped signal from a working diode may be less perfect than textbook illustrations! This is a nonlinear device.

You may wish to reverse the diode in the circuit to see what happens.

The Wavetek generator has an additional feature that is very useful in simulating an AM radio signal. Near the center of the control panel is a push button labeled *amplitude modulation ON/OFF*. Press this button to *ON*. The scope display on Ch 1 should now look something like the lefthand side of the lower figure on p. 2. You can adjust the modulation depth with the knob just to the left of the *ON/OFF* button. The modulated signal is still a high-frequency signal, as described by eq. (2), which contains information about a low frequency that the rest of your circuit should be able to detect, when it is working.

For subsequent tests, you can switch back and forth between the pure sine wave and the modulated sine wave as you find useful.

6b. The Transistor Base

The rectified waveform at testpoint *c* extends from ground to some maximum (or minimum) voltage. But testpoint *d* will have a DC level of about 1.5 V if the 15 V power supply is turned on. So when checking out testpoint *d*, you should use Ch 2 of the scope on both AC and DC to verify that the signal is as expected. Of course, the AC signal at testpoint *d* should be the same as that at testpoint *c*.

6c. The Transistor Emitter

The DC level at testpoint *e*, the transistor Emitter, should be about 0.8V. The AC signal at this testpoint should be very similar to that at testpoints *c* and *d*.

6d. The Transistor Collector

The DC level at testpoint *f*, the transistor Collector, should be about 10 V. The AC signal at this point should be about 10X that at testpoints *c*, *d* and *e* if the amplifier is working properly.

6e. The Circuit Output

Turn on the amplitude modulation of the Wavetek generator for these final tests.

Testpoint *g* should show the same AC signal as at testpoint *e*, but with no DC level. The AC signal here should still show the 1 MHz oscillations within the halfwave form due to the rectification of the diode.

The waveform at testpoint *h* is a low-pass filtered version of the waveform at testpoint *g*, and hence the high-frequency oscillations should be gone now.

If all these tests are successful, remove the input from the Wavetek generator, and you should be able to hear (perhaps rather faintly) the radio signal in your headphones, when they are connected to testpoints *h* and *b*. If the tests were successful but the headphones still sound quiet, substitute the Radio Shack amplifier/speaker for the headphones. You may need to tune your capacitor (and also the pair of inductors) to maximize the signal.

Connect your headphones to testpoint *g* to hear the unfiltered signal. Do **not** connect your headphones to testpoints *d*, *e* or *f*, as the DC levels there could damage your phones.

6f. OPTIONAL: The Effect of Overmodulation

This test is optional because it requires borrowing a 2nd Wavetek generator from another lab station.

The goal is to verify that the conceptually simpler modulation scheme described by eq. (1), and shown in the figure at the top of p. 2, is undesirable.

To study this you need to generate a waveform like that on the lefthand side of the figure at the top of p. 2. Borrow a 2nd Wavetek generator and set its output frequency to about 1 kHz. Connect the output of this generator to the *AM Sweep* input of the first generator. Press the *EXT* button that is just to the left of the *AM ON/OFF* button. The waveform from the 2nd generator now modulates the waveform of the first (which latter should be set to about 1 MHz frequency).

While listening to the output of your amplifier on your headphones, or with the Radio Shack amplifier/speaker, vary the amplitude of the output of the 2nd Wavetek generator. You can view the effect of the modulation on Ch 1 of the oscilloscope (which should still be connected to the output of the first Wavetek generator via a “tee”). “Overmodulation” begins when the “envelope” of the modulated signal reaches all the way to the middle height of the signal, and even goes beyond to create a waveform with a double peak structure.

The quality of the Wavetek generators is not sufficient to produce an overmodulated signal exactly like that shown on the top of p. 2; the modulations become somewhat “squarish” in the case of severe overmodulation.

However, if you have a good ear, you can hear that the audio tone becomes less pure as soon as any overmodulation is present, and that the form of the impurity is the presence of the first overtone of the audio signal (plus even higher overtones in the case of “squarish” overmodulation). If the Wavetek generators were of higher quality, you would hear the fundamental tone completely disappear in the case of full overmodulation, and all you would hear is the first overtone.

The value of this Lab is in the process of making your radio work, so record the details of this process in your Lab notebook. Verify with your Lab partner that both of you can explain the process of amplitude modulation and demodulation that are the bases of AM radio.

