In this lab you will build, test, and utilize a non-inverting amplifier integrated into your very own AM radio receiver. Sweet! The main objective of this lab is to complete the design, construction, and proof-of-concept testing of your very own person AM radio receiver.

The goals of this lab are to:

- Become acquainted with wiring op-amp circuits.
- Learn how to measure input-output amplifier relationships for amplifiers ($V_{out}/V_{in}$).
- Dive into some of the finer points of op-amp specs and limitations
- Design an amplifier for use in an AM radio

1 AM radio basics

As we’ve discussed in class, Amplitude Modulated radio transmission works by forming an envelope around the carrier wave (Figure 1). The envelope carries the audio information. The carrier wave frequency for the AM band in the United States typically spans 560 kHz to 1.2 MHz. These are relatively very high frequencies compared to audio content which is concentrated in a frequency band of 20 Hz (bass) to 5 kHz (treble). The higher the ratio of the carrier frequency to the audio content, the more precise and accurate the audio envelope is.

Figure 1: Principle of Amplitude Modulated radio transmission. The amplitude of the carrier wave is modulated according to the audio signal envelope. Image credit: Horowitz and Hill. The Art of Electronics, 3rd ed.
2 AM radio system overview

Meanwhile, back at the ranch...we started building the AM radio receiver last week. Specifically, you built the LC resonator. The resonance frequency selects the frequency on the dial you’d like to listen to. Now for the remainder! Check out Figure 2 which shows a block diagram of an AM radio receiver. We’ve still to build the amplifier block, the diode rectifier plus RC filter block, and one more amplification block. You’ll complete the design of those.

Figure 2: Block diagram of the AM radio receiver. The LC circuit allows us to tune into one specific frequency being broadcast. This picks up the carrier wave. Next, we (often) must be amplify the AM signal before trying to pick off the envelope containing audio information. Once the signal is amplified, a clever configuration of diode in series with a parallel of $R_p$ and $C_p$ rectifies and smooths the AM radio signal. This allows us to pick off just the envelope containing the audio information. Lastly, we can set the volume using another amplifier before passing the signal into an audio amplifier/speaker for playback.

3 Op-amps: what’s inside the proverbial black box

First let’s take a quick look at op-amps in practice. Look carefully at Figure 3. The 8 electrical contacts extending out of the integrated circuit (IC) allow you to connect to two separate amplifiers. The power connections $V_{cc+}$ and $V_{cc-}$ are shared by both amplifiers. You power one, you power both. Without power, op-amp won’t do anything, so remember to power up! External resistors must be added to complete the design for a non-inverting amplifier (or any other amplifier configuration for that matter).

Figure 3: TL082 op-amp (A) and pinout (B).
The IC has 8 individual contacts—just in time to make a Halloween spider costume or decoration! Note carefully the half-circle at the “top” of the IC that serves as an orientation mark. Just to the left of this mark is pin 1, as indicated in (B). ICs often show a small dot next to pin 1, as is the case for the particular TL082 package shown in (A).

4 Non-inverting Amplifier

Speaking of non-inverting amplifiers, check out Figure 4. To get a first taste of op-amps, we’ll wire up this circuit and quickly look at the input and output to understand how it functions. But first, we interrupt this broadcast for a public safety announcement!

First, do NOT power up the op-amp circuits until they are fully wired. Otherwise you run the risk of having something mis-wired, which can lead to a nicely toasted op-amp. The corollary is that you should always power down your circuit before un-wiring it and returning components to the bins.

Also, you’ll quickly notice that the pins extending from the chip are easily bent. When the pins are bent, getting the chip into and out of your board can be a pain. So, take care of your chip, be careful not to bend the pins. Use a small screwdriver to gently wedge underneath the IC then gently rock it free. Easy does it.

![Non-inverting Amplifier](image)

**Non-inverting Amplifier**

Figure 4: Non-inverting amplifier configurations. The voltage gain of non-inverting amplifier is \( G_v = (1 + R_f/R_i) \).

And we now return to our regular programming...

1. Build the non-inverting amplifier shown in Fig. 4. Use \( R_f \approx 5.6 \, \text{k}\Omega \), \( R_i = 1 \, \text{k}\Omega \), and \( R_3 \approx R_f|R_i \). For \( V_{in} \), use a 2 V p-p, 1 kHz sine wave. \( \pm V_{cc} = \pm 15 \, \text{V} \). Display the input and output...
voltage sinusoids $V_{in}$ and $V_{out}$ simultaneously on the oscilloscope. Carefully sketch what you see.

2. What is the phase relationship between the input and output?

3. Measure and report the voltage gain.

4. Compute the theoretical voltage gain of this amplifier.

5. Compare the measured and theoretical voltage gain values. Compare and contrast—do they pass the sanity check?

6. Take a look at “Output voltage swing” specs on page 3 of the TL082 datasheet (available on the course website, or just google it). The output voltage swing specifies the maximum and minimum voltage the op-amp can achieve provided the op-amp is powered by ±15 V. Using this information, predict the amplitude of the input signal for which you expect to see saturation (aka clipping) begin to occur. Now, slowly increase the amplitude of the input signal. What is the actual amplitude of the input signal when clipping began to occur? How accurate was your prediction compared to what you measured? Does it pass the circuits sanity check?

5 AM carrier wave amplifier

Now that you’re experienced with building a non-inverting amp, you are ready to design, build, and test the amplifier section of your AM radio receiver. Yay! The job of the amplifier is to boost the signal output from your LC resonator to an amplitude that is compatible with the downstream diode, which requires $\approx 0.6 - 0.7$ V to “turn on.” So the voltage gain of the amplifier should be sufficient to achieve an amplifier output signal of $\geq 1.5$ V amplitude (3 V pk-pk). 1.5 V leaves a little headroom to make sure your diode can go into forward conduction at about 0.6 V. Of course you can’t go too bonkers with your voltage gain, else you run the risk of saturation, which is really bad for audio applications (unless you are Jimi Hendrix and want to create guitar distortion effects!). Lastly, you know only an approximate range of how large the output signal will be from the LC tuning section, so you’d be very wise to make the voltage gain adjustable. That’s easily achieved with a pot, of course.

In your design, make sure to use a TL082 variety of op-amp for this application. Of the many possibilities (LM324, UA741, etc) why the TL082 you ask? Great question! Op-amps are like cars, each has pros and cons. The big pro of the TL082 for this AM radio application is that it a speedy little guy. It wide gain-bandwidth product of 4 MHz and high slew rate of 13 $\mu$V/s. These features are highlighted on the front page of the datasheet. What on Earth are these features about, you ask? Another great question!

The maximum possible rate of change of the output signal is called the slew rate ($SR$).

$$\text{SlewRate} = \max \left| \frac{dV_{out}}{dt} \right|$$
The gain-bandwidth product specifies the maximum gain that be achieved at a certain frequency.

\[ GBW = (\text{maximum voltage gain achievable}) \times (\text{signal frequency}) \]

So let’s say we’ve got a carrier wave at a frequency of 200 kHz and an amplitude of 0.5 V to be amplified. Let’s say we’d like to amplify by a factor of 10, so that the output is a 5 V, 200 kHz sine wave, i.e., the desired \( V_{out} = 5 \cos(2\pi \times 200000 \times t) \). Can the op-amp actually achieve this output? Depends on the gain-bandwidth product and the slew rate!

For the \( GBW \) we want to have a gain of 10 at a frequency of 200 kHz. Is \( 10 \times 200 \text{ kHz} \leq 4 \text{ MHz} \) (our device’s spec)? Yes! We are asking for 2 MHz gain-bandwidth product and our op-amp can give us up to 4 MHz, so we’re good there. Other op-amps have much lower \( GBW \) values, so be careful.

Next, what about the slew rate? We expect that \( \frac{dV_{out}}{dt} = \frac{4}{\pi} \times 100000 \times -\sin(2\pi \times 200000 \times t) \). Thus the maximal value of the derivative is \( 5 \times 200000 \times 10^{-6} \text{V/s} = 1 \text{ V/µs} \). Our device spec is a slew rate of 13 µs. So the TL082 is plenty fast—in fact we have a safety factor of about 8-13 in this example (scroll down to page 3 of the datasheet and look for slew rate minimum and typical specs).

\textbf{In summary, your task is to design a variable voltage gain amplifier to amplify the LC oscillator signal up to an amplitude that will be compatible with the diode rectifier and smoothing RC circuit downstream. Make sure you avoid saturation too.}

6 Smooth move: Diode and RC demodulation

Take a look at Lab 4, section 2. Get some practice with this section of the circuit by building the circuits shown in Lab 4 Figures 4 and 6. Use an 1N4148 diode. Out of all the diodes out there (1N4001, 1N4007, 1N918), why the 4148 you ask? Because it is made for fast switching applications—the datasheet highlights this feature. 100 kHz is pretty darn fast. You are essentially switching the diode on and off at a period of 1/100 kHz = 10 µs. How fast can your hand turn on and off a light switch? Probably not 100,000 times per second. Even world champion cup-stacker and current W&L student Will Orell can’t manage that feat: \( \text{https://www.youtube.com/watch?v=VyyscuIq56I} \).

Once you understand the operational principle, it’s time to choose a value for \( R_p \) and \( C_p \) in Figure 2. The guiding principle here is that this parallel combo needs to “compute” the audio signal envelope by smoothing out the carrier wave signal. Smoothing is a close relative of low-pass filtering. You should design this part of the circuit such that audio frequencies \( (f_{audio} \leq 5 \text{ kHz}) \) are retained, i.e., not smoothed out. Only the carrier wave ticking along at \( \approx 100 - 200 \text{ kHz} \) should be smoothed out. A couple of guiding principles to help you:

1. Firstly, you can quickly convince yourself using limiting cases that this part of the circuit acts like a low pass filter. Draw the limiting cases to convince yourself this is true.
2. Second, you can show quickly that the parallel equivalent impedance of $R_p$ and $C_p$ is given by:

$$Z_p = R_p \left( \frac{1}{1 + j\omega R_p C_p} \right)$$

There's that RC term again, namely $R_p C_p$. And, oh my word, if that term inside the parenthesis doesn't look just like a (fill in the blank)!

3. Third, the resistor $R_p$ is generally chosen to be a modest value. Something around 1 kΩ would do.

4. Lastly, put the pieces of the puzzle together to choose an appropriate value for $C_p$.

If all goes according to plan, you should see a picture on your oscilloscope like the one in Figure 5. Note the scale of 500 mV/div; the amplitude is therefore estimated to be about 1 V (just enough to turn on the diode). The blue trace shows the output from the smoothing section, probe attached to the “top” of the $R_p C_p$ parallel combo. Note that this blue trace captures the envelope of the AM carrier wave, albeit imperfectly.

![Figure 5: AM radio demodulation. Yellow trace is the input to the diode = output from the carrier wave amplifier. Blue trace is the output measured across the smoothing cap and resistor parallel combo.](image-url)
Almost there! We’ve now recovered the audio envelope, as the voltage measured across the smoothing capacitor. It might be possible to run this signal straight into an audio amplifier-speaker combo. And it might (probably would) work. However, it would be poor form to do this circuits-wise. Why’s that, you ask? Because the moment you connect the audio amplifier into the circuit, you just put another element in parallel with $R_p$ and $C_p$. That’s a dangerous operation because you just spent a good bit of time carefully choosing $R_p$ and $C_p$ to achieve a cutoff frequency of $\approx 5$ kHz. There’s a better way. Use another op-amp as a buffer between the smoothing components and the audio amp. A buffer is great because it allows you to cascade sections together in an ideal way—the audio amplifier will no longer interfere with the operation of the smoothing cap. You could also get a little fancy and use another adjustable gain non-inverting amp to control the volume.

So your last design task of the day is complete construction of final amplifier.

When you are ready, make your own AM broadcast station! We’ll need to make sure your LC resonance frequency is tuned to the transmitter...or the transmitter is tuned to the resonance frequency of your LC circuit, which you determined last week. We’ll do the latter, as we have on hand our very own radio AM transmitter (see Section 10).

8 Make your own AM broadcast station

Lexington is beautiful (especially during autumn!), but is not exactly blessed with heaps of AM radio stations. In fact, there is only 1 on the dial. Never fear - we’ll make our own broadcast! How to do this? You need but two items: 1) BK precision 4014B function generator and 2) audio playback source (smart phone, laptop, etc.)1. Follow the step-by-step picture directions in Figure 6. The output of your function generator is now an Amplitude Modulated signal with known carrier frequency. You can connect a coil (inductor) between the two function generator leads to act as an antenna. In case you are wondering “what’s inside the box” to make an AM station, check out Section.

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1Thanks to Simon Marland and Daniel Rhoades for their keen observations leading to this easy broadcast method
Figure 6: Create your own AM station using the BK Precision 4014B functional generator. (A) Plug in your audio playback source to the *Modulation In* jack. (B). Set the carrier frequency to your resonance frequency. (c) Click the “MODUL” button (highlighted in red square), then select Amplitude Modulation (F2; red arrow).
9 The Report

Your report should describe the design principles and demonstrate proof of concept of how your amplifier and diode rectifier plus RC smoothing components work in AM radio. To this end, be sure to:

1. Carefully diagram your amplifier section, describe operational principles. What are achievable voltage gains of this amplifier? What are rationale for selecting this (range of) voltage gain. State all relevant theory and show calculations as necessary.

2. For the RC smoothing circuitry, what did you choose for resistance and capacitance values? What were your rationale for choosing those values? Per usual, state all relevant theory and show relevant calculations.

3. Zoom back out to show your reader the whole system. Describe how the pieces all go together to make a working AM radio.

4. Suggest improvements to the system—design, construction, better choice of voltage gain and/or other component value choices, user-friendly operation, etc.

5. Proof of concept: There are 2 means by which you should demonstrate this.

   • Firstly, show input vs. output for your various “functional blocks.” That is, show the input and output of your amplifier on the oscilloscope. A photo/screen shot is sufficient. Be sure to carefully label/annotate the photograph to highlight and make obvious to your reader the amplifier in action. Do the same for the rectifier-plus-RC smoother (low pass filter). Show the input into that block (= output from the amplifier) simultaneously with the output from the RC LPF. Again, carefully annotate your o’scope screenshot/photograph to clearly illustrate the function of the diode + RC circuit.

   • Music is best live. So, take a short video of your AM radio in action. It would be incredibly helpful to have a walk-through of what’s on the breadboard, then a live demonstration of music playing....icing on the cake! Best video wins a small circuits-appropriate prize!
Appendix: DIY AM broadcast station

The curious cat may be wondering: how do you make an AM signal in the first place. What’s the magic inside the function generator? The trick is to use an op-amp and JFET as shown in Figure 7. If you stare at this circuit for a second, you’ll probably think Hey, this is similar to the non-inverting amp I built today. Indeed, it is! The trick, however, is to replace the resistor we normally label as $R_i$ with a JFET (*junction field effect transistor*). The JFET is a device that allows more or less current to flow based on the voltage driving the gate. If we use our audio signal to drive the gate, then the effective resistance of the JFET changes according to the audio signal. In effect, we have made a variable gain amplifier, whose gain varies with the audio signal. Voila—and amplitude modulated signal!

One last detail: you might also notice the battery in series with the audio source driving the JFET. This is called “biasing” the FET and basically puts it in conducting state. Basically, we have to turn on the FET to flow some current, then add the audio signal in series to flow a little more or a little less current through the FET.

Figure 7: AM signal generation. This configuration is similar to non-inverting amplifier, except one resistor is replaced by a FET driven by the audio signal.