# EECS 216 Winter 2008
## Lab 3: AM Radio
## Part II: In-Lab & Post-lab Assignment
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## 1 Introduction

In this laboratory you will assemble and test a working superheterodyne AM radio consisting of a front-end (antenna, tunable RLC circuit and mixer), an IF filter, an envelope detector, a DC blocking capacitor and a speaker; see Fig. 3.0.2. The In-Lab data collection and Post-Lab data analysis will focus on the actions of the mixer, IF filter, envelope detector and DC blocking capacitor. Laboratory work to study the characteristics of the antenna and tunable RLC circuit in the front-end is included, but is *optional*. Assuming that you have successfully completed the Pre-Lab, you should be able to complete comfortably the required portion of the In-Lab work in a single 3-hour laboratory period. The EECS 216 Course Syllabus indicates a second make-up period for this lab (AM Radio); you should only need it for pursuing the optional portion of the lab.

As in Lab 2, much of your circuit will be pre-built so that your time in the laboratory is focused on verifying the systems theory you have learned in lecture. You will know your radio is working when you receive the AM signal being transmitted in the laboratory. To further confirm that your radio is functioning, you will also be asked to receive a commercial radio station operating at 1600 KHz.

## 2 Parts List

Table 2.1: Parts List for the AM Radio Lab

| Resistors | Capacitors | Other |
|---|---|---|
| 1 KΩ (IF filter) | 1.5 nF (IF filter) | radio font-end |
| 120 Ω (IF filter) | 2.2 nF (envelope detector) | Op-Amps LF356N (2) (IF filter and output amplifier) |
| 10 KΩ (IF filter) | 220 $\mu$F (DC blocking capacitor) | Diode 1N34A (envelope detector) |
| 75 KΩ (envelope detector) | 0.1 $\mu$F (4) (op-amp power supply lines) | Audio speaker |
| 20 KΩ (output amplifier) | | |
| 5.1 KΩ (output amplifier) | | 10x scope probe |
| 91 KΩ (envelope detector) | | loopstick antenna and RLC circuit |

**Dual-In-Line Package (M and N)**



00564629

**Order Number LF356M, LF356MX, LF355N, or LF356N**
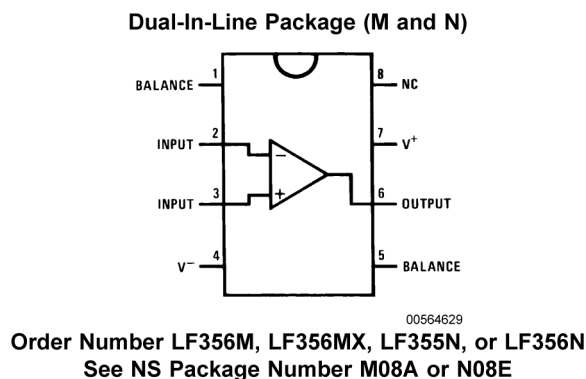**See NS Package Number M08A or N08E**

Figure 2.0.1: Pinout Diagram for the LF356N Op-Amp

# 3 Radio Block Diagram & Protoboard Layout

Consider the superheterodyne AM radio block diagram shown in the Pre-Lab and repeated below for convenience. This diagram shows four functional elements: (1) pre-built font-end, (2) IF filter, (3) envelope detector, and (4) output amplifier.
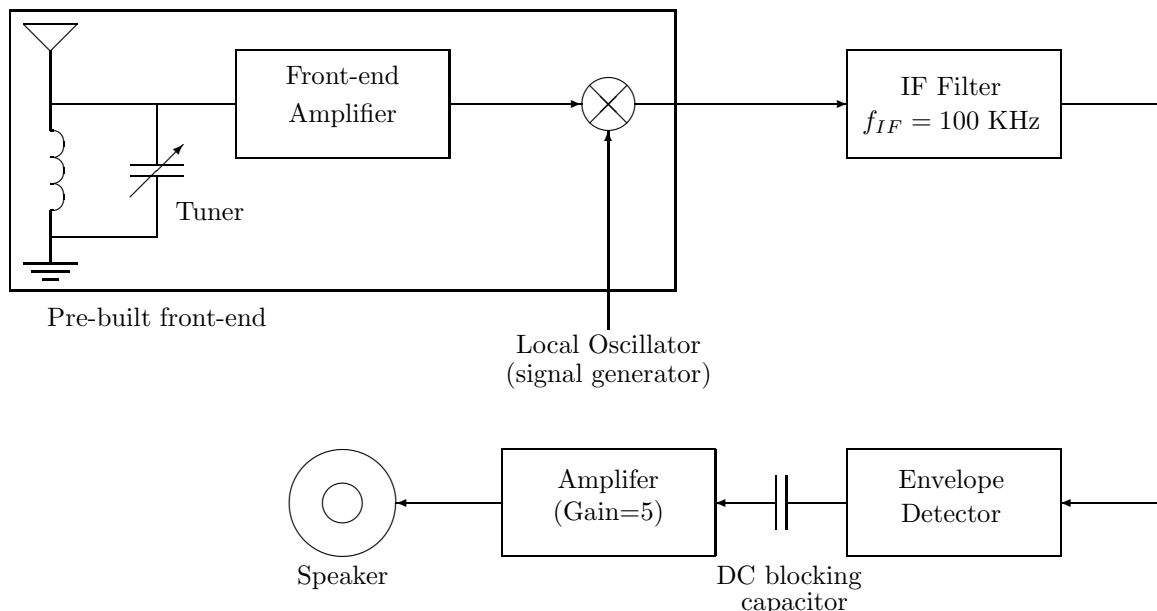


Figure 3.0.2: AM Superheterodyne Radio Block Diagram

The first element is an integrated module and one of them has been supplied to each lab bench. The last three of these elements have been laid out on the protoboard by your GSI. In order to facilitate debugging, the protoboards have been laid out in the manner shown in Fig. 3.0.3. Each op-amp is installed so that the circle indent on its face is located on the left side of the chip when viewing the layout. The various subsystems have not been interconnected. You will be asked to do this at the appropriate time. *Even though your GSI has pre-built the major circuit elements, so that you can focus on the systems aspects in the lab, it is still your responsibility to double check everything.* If you have problems, request help from your GSI.
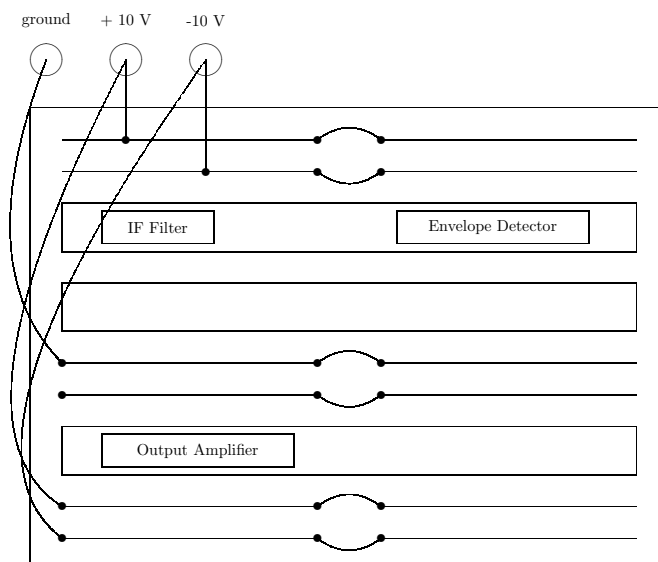
Figure 3.0.3: Protoboard Layout. Be very careful **<u>not</u> to exceed $\pm$ 10 V** on the supply voltages!

# 4    Required In-Lab AM Radio Assembly & Testing

The circuit elements shown on the protoboard in Fig. 3.0.3 together operate as a bandpass (IF) filter, an AM demodulator (envelope detector), and an output amplifier that will be used to drive a speaker. When the input to the IF filter is an AM signal operating within the passband of the filter,

$$V_i(t) = (A + bx(t))\sin(2\pi f_c t + \phi),$$

the output of the amplifier circuit should be a signal proportional to $x(t)$.

**Lab Notes:**

(a) For Task 1, make sure that the function generator (use the UTILITY button) is set in the High Z load mode. For other tasks, where you are using the function generator to produce AM modulation, make sure the generator is set on the 50 $\Omega$ load mode.

(b) Make sure that both channels 1 and 2 of the oscilloscope are set for DC coupling and with probe 1x.

## 4.1    In-Lab Task 1: IF Filter Characterization

(a) Verify the construction of the IF filter shown in Fig. 4.1.1; it should be located on the protoboard in the location indicated in Fig. 3.0.3. At this time, do NOT connect this circuit to any of the other components on the protoboard.

(b) Using the oscilloscope and function generator, measure and record the *magnitude* of the frequency response function $|H(j\omega) = |\frac{V_o(j\omega)}{V_i(j\omega)}|$ of the IF Filter at the thirteen (13) frequencies given below. In each case, use a sinusoid with a 600 mV peak-to-peak amplitude. Note that you are not asked to record phase data.

**Remark:** If your IF Filter is properly constructed, then you should observe that it operates as a bandpass filter, with a center frequency in the vicinity of 100 KHz. The basic *shape* of the measured frequency response function should *approximately* match that of your calculations in Pre-Lab Problem 3.2.
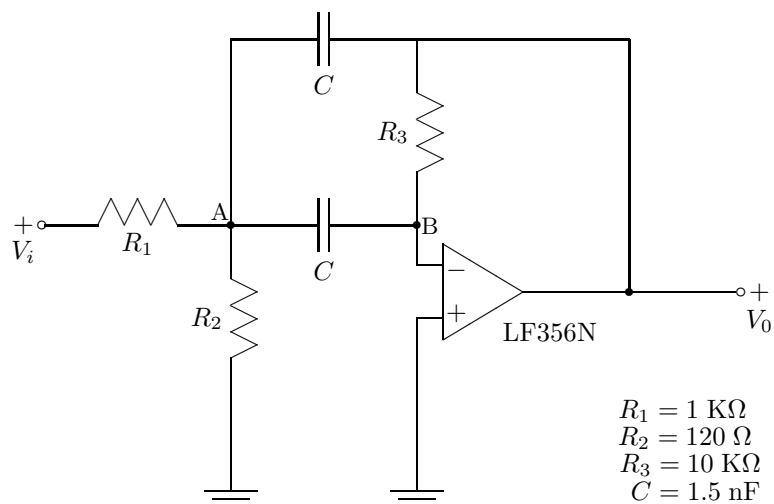
Figure 4.1.1: IF Filter

Table 4.1: IF Filter Frequency Response Function

| $f$ (KHz) | Measured $|H(j\omega)|$ |
|-----------|-------------------------|
| 20        |                         |
| 30        |                         |
| 70        |                         |
| 80        |                         |
| 90        |                         |
| 100       |                         |
| 110       |                         |
| 120       |                         |
| 130       |                         |
| 140       |                         |
| 150       |                         |

## 4.2   In-Lab Task 2: Envelope Detector

(a) Verify the construction of the envelope detector circuit shown in Fig. 4.2.1, which should be found on the protoboard in the location indicated in Fig. 3.0.3. At this time, do NOT connect this circuit to any of the other components on the protoboard.

(b) Test the operation of your envelope detector using your function generator and oscilloscope by applying the following input to the circuit[1]

$$V_i(t) = [4 + 2\sin(2\pi f_s t)]\sin(2\pi f_{IF} t) \text{ V} \tag{4.2.1}$$

where $f_{IF} = 100$ KHz and $f_s = 1$ KHz. *Don't forget to switch your function generation to the 50 $\Omega$ load mode when using the modulation function.* Observe the input on the oscilloscope by setting the horizontal sweep time to 200 $\mu$s/division and press the RUN/STOP button to freeze the waveform on the screen of the scope. Because of the way this scope operates, it may take several tries to get a nice

---

[1]Recall the modulation depth of $x(t) = (A + bs(t))\cos(\omega_c t + \phi)$, specified as a percentage, is defined as $\frac{\max(bs(t)) - \min(bs(t))}{2A} \times 100\%$, as in Lab 2.
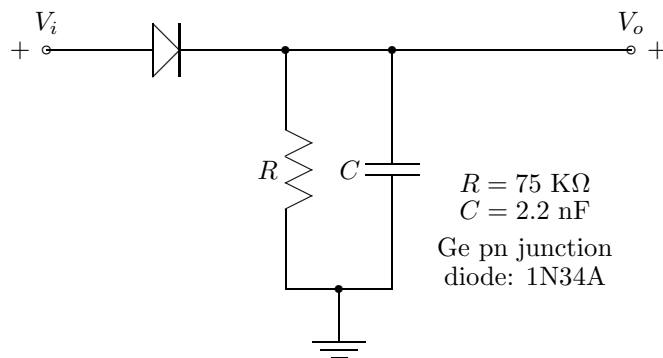
Figure 4.2.1: Envelope Detector

clean looking result. Verify visually that the waveform is correct (i.e. $1+0.5\sin(2\pi f_s t)$ V). **Record a graph of the waveform using the ScopeConnect software.**

Now change the horizontal sweep time to 5 $\mu$s/division. Press the RUN/STOP button to freeze the waveform on the screen of the scope. Verify that the carrier frequency is 100 KHz. Now view simultaneously on the oscilloscope the circuit's input and output (set the horizontal sweep time to 200 $\mu$s/division and press the RUN/STOP button to freeze the waveforms on the screen of the scope). **Record a graph of the waveform using the ScopeConnect software.**

(c) Repeat part (b) with the modulation changed to a triangular wave (4 V p-p at a frequency of 1 KHz). **This time, you do NOT have to record any data.**

(d) Recall from Lab 2, that for the envelope detector to work well, the capacitor $C$ must discharge little during the half cycle when the diode is reverse biased, i.e., $RC \gg 1/f_{IF}$, AND that the signal must change slowly in comparison to the time constant of the envelope detector, i.e., $RC \ll 1/f_s$. These conditions can be most easily satisfied when the ratio of $f_{IF}$ to $f_s$ is large. For the parameters used above (i.e., $f_{IF} = 100$ KHz and $f_s = 1$ KHz), we have

$$RC = (75000)(2.2 \times 10^{-9}) = 1.65 \times 10^{-4} \gg \frac{1}{f_{IF}} = 10^{-5} \tag{*}$$

and

$$RC = (75000)(2.2 \times 10^{-9}) = 1.65 \times 10^{-4} \ll \frac{1}{f_s} = 10^{-3}. \tag{**}$$

Consequently the envelope detector should work properly.

The information signal in a commercial AM broadcast is limited to an absolute bandwidth of 5 KHz. As $f_s$ increases from KHz to 5 KHz, the condition (**) becomes less well met, and some degradation in the performance of the envelope detector can be observed. Repeat the measurements in (b) for $f_s = 5$ KHz and observe that the output of the envelope detector does not fit the real envelope as well as it does when $f_s = 1$ KHz. **Record a graph of the output of the envelope detector using the ScopeConnect software.**

## 4.3 In-Lab Task 3: Output Amplifier

(a) Verify the construction of the amplifier circuit shown in Fig. 4.3.1, which should be found on the protoboard in the location indicated in Fig. 3.0.3. At this time, do NOT connect this circuit to any of the other components on the protoboard.
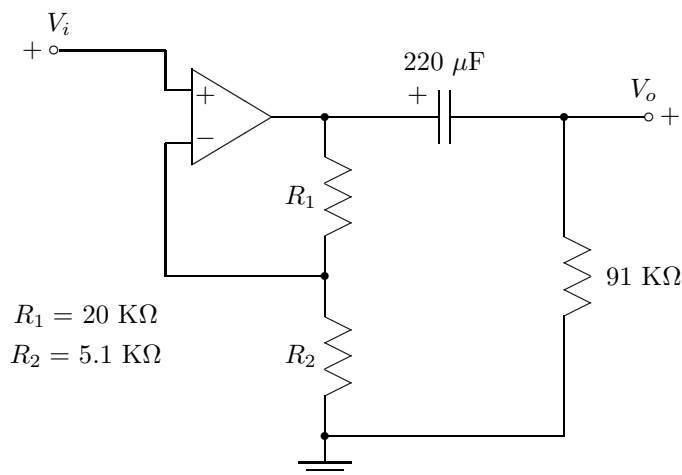
Figure 4.3.1: Gain 5 Amplifier with DC Blocking Capacitor

(b) Use your function generator and oscilloscope to test the amplifier and measure its voltage gain,

$$|H(j\omega)| = \left|\frac{V_o(j\omega)}{V_i(j\omega)}\right|,$$

at a frequency of 5 KHz (set function generator amplitude to 500 mV peak-to peak). **Record the gain value.** It will <u>not</u> be exactly 5.0. *Note: Do you have the proper impedance setting on the function generator?*

## 4.4   In-Lab Task 4: Interconnections

(a) Interconnect the IF Filter, the envelope detector, the DC blocking capacitor and the output amplifier as shown in Fig. 3.0.2.

(b) Test the entire circuit by applying the following AM signal to the input of the IF Filter:

$$V_i(t) = [A + 0.5A\sin(2\pi \cdot 1000t)]\sin(2\pi f_c t) \text{ V}, \tag{4.4.1}$$

where $2A = 600$ mV peak-to-peak and $f_c$ is equal to 50 KHz, 70 KHz, 90 KHz, 100 KHz, 110 KHz, 140 KHz, and 200 KHz. *Make sure your function generator is set to the 50 $\Omega$ load mode when using the modulation function.* For each of these frequencies, use the oscilloscope to observe the output signal after the DC blocking capacitor. In each case, the output should be a sinusoid. Record the frequency and peak-to-peak amplitude of this sinusoid in the tabular format shown below in Table 4.2. For the lowest and highest frequency values, you may have difficulty seeing a signal. If this is the case, record "not observable" in your table. *It is suggested that you start at 100 KHz and work down in frequency; then return to 100 KHz and work your way up.*

## 4.5   In-Lab Task 5: Full Radio with Transmitter Located in the Lab

(a) Each bench is supplied with a pre-built front-end. Connect the pre-built front-end to your fully assembled circuit (see Fig. 3.0.2). The front-end contains the antenna/tuned RLC circuit described in the Pre-Lab, Section 2.2, a field effect transistor (FET) amplifier and a mixer (i.e. a multiplier). A drawing of the pre-built front-end box is shown in Fig. 4.5.1 below. The tuning control knob on the pre-build front-end box controls the variable capacitor setting of the front-end loopstick antenna/RLC

Table 4.2: AM Demodulator Performance

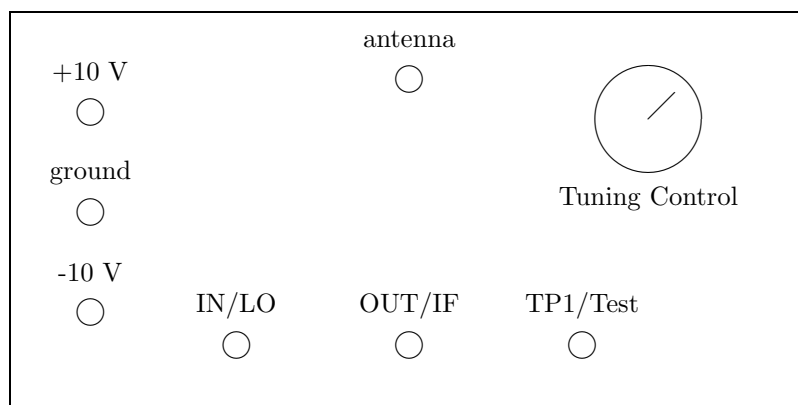| $f_c$ (KHz) | Output frequency (KHz) | Output voltage (V p-p) |
|---|---|---|
| 50 | | |
| 70 | | |
| 90 | | |
| 100 | | |
| 110 | | |
| 140 | | |
| 200 | | |

Figure 4.5.1: Pre-built Radio Front-end

circuit. Also connect the white speaker on your lab bench to the output of the output amplifier on your protoboard.

The front-end should be connected to your protoboard circuit and lab instruments as follows:

1. $\pm 10$ V and ground connected via banana plugs to the lab power supply.

2. IN/LO connected via a BNC to the output of the function generator.

3. OUT/IF connected via a BNC (with clips on one end) to the input, $V_i$ of your IF filter (see Fig. 4.1.1).

4. Test point can be left unconnected.

5. In order to improve reception, a short wire antenna can be attached to the loopstick antenna. This wire antenna is connected to the pre-built front-end box via a phono-plug. If it is not already inserted, insert the phono plug into the antenna receptacle on the pre-built front-end box. The phono-plug wires (white and black) can be left dangling but should not contact one another or any other components.

(b) An AM transmitter has been set-up in a corner of the laboratory and is transmitting an interesting signal of the form

$$x(t) = (A + bm(t))\sin(2\pi f_c t + \phi) \qquad (4.5.1)$$

When the font-end tuning capacitor and LO are set properly, you will hear an unmistakable signal emanating from the speaker.

Set the LO (i.e., the function generator) to a 430 kHz sinusoid and set the peak-to-peak voltage of the sinusoid to be 50 mV. Adjust the tuning control knob on the pre-built font-end until you hear the signal that is being generated by the transmitter in the lab. Adjust the tuning control knob to maximize the volume of this signal. Also make *small* adjustments of the LO frequency to maximize the volume of your signal.

*If the sound is too loud, note that you can de-tune the capacitor in the front end unit so as not to disrupt your fellow lab mates as much. It is the only volume control knob you have in this circuit.*

(c) Based on the LO frequency that yields the loudest volume, and recalling that $f_{IF} \approx 100$ kHz, find the two possible carrier frequencies, $f_c$, at which the local transmitter might be transmitting. **Hint:** $f_c = f_{LO} \pm f_{IF}$.

Table 4.3: Possible Carrier Frequencies

| $f_{LO}$ (KHz) | Possible $f_c$ (KHz) | Possible $f_c$ (KHz) |
|---|---|---|
|  |  |  |

(d) Determine which of these frequencies is the actual carrier frequency, $f_c$. Here is a strategy for doing this: For each carrier frequency, determine the possible LO frequencies to center the signal in the passband of the IF filter ($f_{LO} \approx 430$ kHz will be one possible LO frequency). **Hint:** Use $f_{LO} = f_c \pm f_{IF}$. Successively set $f_{LO}$ to the possible LO frequencies values and note whether or not you hear a signal at that LO frequency. From this information, you can determine the local transmitter's actual carrier frequency. For now, record the data and you can deduce the correct carrier frequency later in the Post-Lab analysis.

## 4.6   In-Lab Task 6: Full Radio with Transmitter a Local Radio Station

(a) Compute and record the LO frequencies that should be used to listen to a local commercial AM radio station broadcasting at a carrier frequency of 1600 kHz.

Table 4.4: Tested LO Frequencies

| $f_{LO}$ (KHz) | Signal Heard or Not |
|---|---|
| 430 KHz | Yes |
|  |  |
|  |  |

(b) *Turn the tuning knob on the pre-built front-end box clockwise to its maximum position*[2]. Set the LO to one of the frequencies computed in part (a) and then *hold the bare end of the white antenna wire between your thumb and index finger* (your body acts as a large antenna to improve reception) and listen to the commercial AM radio broadcast! Repeat using the other possible LO frequency. *Ask the GSI to come to your bench and verify that your radio is operating properly. This is all you need to do. There is nothing to record.*

**Remark:** You will find that the demodulated local AM radio signal is very faint. In part, this is due to poor reception in the lab. You may wish to boost the signal. You can do this in two ways.

- In the output amplifier of Fig. 4.3.1, replace the 20 $\Omega$ resistor with a 40 $\Omega$. This will roughly double the gain.

- Ask your GSI for suggestions on adding a power amplifier to your circuit.

It is emphasized that neither of these is required. Only pursue this final step for fun and if you have time.

## Congratulations! You have built a working AM radio.

# 5 Required Post-Lab Assignment

## 5.1 Post-Lab Problem 1 (IF Filter Characterization)

(a) Complete the `Measured` column of Table 5.1 using your In-Lab data from Table 4.1. Complete the `Computed` column by evaluating the magnitude of the frequency response function, $|H(j2\pi f)|$, for the IF Filter of Fig. 4.1.1 at the indicated frequencies. Recall that you computed this frequency response function in the Pre-Lab.

(b) Plot your measured results together with the theoretically calculated curve of $|H(j2\pi f)|$. The peak magnitude and center frequency may vary slightly from the values calculated in the Pre-Lab. These differences occur because the actual resistor and capacitor values are not exactly equal to their nominal values, and the op-amp behavior may not be ideal as was assumed in the calculations.

## 5.2 Post-Lab Problem 2: Envelope Detector

Turn in the three graphs you recorded during the In-Lab portion using the ScopeConnect software.

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[2]In order to be resonant at a carrier frequency of 1600 KHz, the front-end variable capacitor would need to be set to a value of about 10 pF (i.e.,

$$f_{res} = \frac{1}{2\pi} \frac{1}{\sqrt{LC}} \text{ Hz}$$

and $L$=960 $\mu$H). When the front-end variable tuning capacitor is fully open (i.e., minimum overlap between the pairs of plates), it has a capacitance of about 13 pF. In addition, there is some "stray" capacitance inside the pre-built front-end circuit that adds an additional increment to this value. Thus at the high end of the AM band (i.e., around 1500 kHz and above), one cannot reduce the variable capacitance to achieve resonance and maximize the signal strength. The best one can do is to get as close to resonance as possible by setting the variable capacitor to its minimum value, i.e., by turning the knob fully clockwise.

Table 5.1: IF Filter Frequency Response Function

| $f$ (KHz) | Measured $|H(j\omega)|$ | Computed $|H(j\omega)|$ |
|-----------|-------------------------|-------------------------|
| 20        |                         |                         |
| 30        |                         |                         |
| 70        |                         |                         |
| 80        |                         |                         |
| 90        |                         |                         |
| 100       |                         |                         |
| 110       |                         |                         |
| 120       |                         |                         |
| 130       |                         |                         |
| 140       |                         |                         |
| 150       |                         |                         |

## 5.3 Post-Lab Problem 3: Output Amplifier

(a) Give the gain value recorded In-Lab.

(b) Compute the frequency response function $H(j\omega)$ of the amplifier in Fig. 4.3.1. Compare the measured and calculated voltage gain at a frequency of 5 KHz. **Note:** They will NOT be exactly the same.

## 5.4 Post-Lab Problem 4: Interconnection

Turn in the table below completed with your In-Lab measurements.

Table 5.2: AM Demodulator Performance

| $f_c$ (KHz) | Output frequency (KHz) | Output voltage (V p-p) |
|-------------|------------------------|------------------------|
| 50          |                        |                        |
| 70          |                        |                        |
| 90          |                        |                        |
| 100         |                        |                        |
| 110         |                        |                        |
| 140         |                        |                        |
| 200         |                        |                        |

## 5.5 Post-Lab Problem 5: Full Radio with Transmitter Located in the Lab

(a) Provide the two possible carrier frequencies, $f_c$, at which the local transmitter might be transmitting.

(b) State which of these frequencies is the actual carrier frequency, $f_c$ and explain why.

## 5.6 Post-Lab Problem 6: Full Radio with Transmitter a Local Radio Station

(a) Provide the LO frequencies that can be used to listen to a commercial AM radio station broadcasting at a carrier frequency of 1600 kHz, with the IF filter centered at 100 KHz.

# End of Required Post-Lab!

# 6   Optional In-Lab AM Radio Assembly & Testing Exercises Dealing with the Font-End Antenna/RLC Tuning Circuit

These optional exercises are aimed at helping you to understand antennas from a circuit point of view. Completing this section will neither improve nor detract from your overall lab grade.

Recall that the front-end antenna/RLC tuning circuit consists of a loopstick antenna connected in parallel to a variable capacitor as shown in Fig. 6.0.1 below. In the radio, the voltage dropped across the variable capacitor serves as the input to the FET front-end amplifier. Recall that the Thevenin equivalent of the loopstick antenna is a voltage source, $V_{ant}$, in series with an inductor ($L$) and a resistor ($R_{ant}$). $V_{ant}$ is proportional to the strength of the received radio signal. At each lab bench, there is a tuning circuit like the one shown below, except that the wire connecting points A and B has been removed, and points A and B are accessible via a BNC connector. The circuit has been mounted and made available to you so that you can see how it works without taking apart the pre-built front-end box.
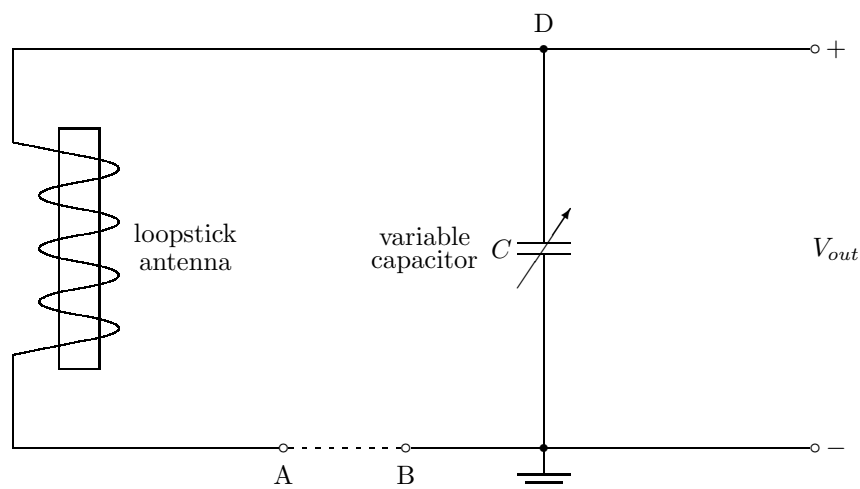


Figure 6.0.1: Antenna/Font-end RLC Tuning Circuit (pre-amplifier and mixer not shown)

You will be connecting the function generator to points A and B via the BNC connector to emulate the voltage, $V_{ant}$, that would be produced by a received signal. You will measure $V_{out}$ and demonstrate that this resonant RLC circuit acts as a tunable bandpass filter. From the measured bandwidth of the filter, you will determine the loopstick resistance, $R_{ant}$. You will also make similar measurements in the time-domain by applying a step input voltage across points A and B.

Connect the function generator via a BNC cable to points A and B in Fig. 6.0.1. Place the scope input across the variable capacitor to measure $V_{out}$. Use the 10x scope probe (these are grey instead of black) for this measurement. These probes are specially designed to have low capacitance (i.e., about 13 pF) so they will not unduly affect the total capacitance (i.e., capacitance of the variable capacitor + capacitance of the probes) that the loopstick antenna sees. Because we are using a 10x scope probe, on the scope you should press the appropriate channel button (1 or 2) and change the Probe setting from 1x to 10x so that your measurements are displayed correctly.

We want to determine two things: the resonant frequency of the circuit and the equivalent resistance of the inductor, $R_{ant}$, both at a variety of capacitor values (positions). We will first perform a time-based experiment. We have used an LCR meter in the laboratory to measure the inductance of the loopstick antenna and obtained a value of 960 $\mu$H. You will use this value when doing the calculations in the problems below. Also note that the signal generator has a Thevenin equivalent circuit consisting of an ideal voltage source in series with a 50 $\Omega$ resistor. When the function generator output is set to High Z mode, the value of this ideal voltage source equals the voltage setting of the function generator. Conversely when the function

generator output is set to 50 $\Omega$ load, the value of this ideal voltage source equals twice the voltage setting of the function generator.

## In-Lab/Post-Lab Problem 7:

Use the function generator to generate a pulse of frequency 100 Hz, width 1 ms, that goes from 0 V (low) to 1 V (high). Recall that the step response is given by Eqs. (2.2.9)-(2.2.12) in Section 2.2.2 of the Pre-Lab. These equations are repeated below for your convenience. Note that the response consists of a DC component (i.e. 1 V) plus a damped sinusoidal term (i.e., $(\sin\phi)^{-1}e^{-(R/2L)t}\sin(\omega t + \phi)$).

$$V_{out}(t) = [1 - (\sin\phi)^{-1}e^{-(R/2L)t}\sin(\omega\,t + \phi)]u(t) \tag{6.0.1}$$

where

$$\omega = \sqrt{\omega_{res}^2 - (R/2L)^2}\ \text{rad/s} \tag{6.0.2}$$

$$\phi = \tan^{-1}\left(\frac{\sqrt{\omega_{res}^2 - (R/2L)^2}}{(-R/2L)}\right) \tag{6.0.3}$$

$$\omega_{res} = \frac{1}{\sqrt{LC}}\ \text{rad/s} \tag{6.0.4}$$

Start with the capacitor fully closed, i.e., the plates completely overlapped and the capacitance at a maximum. Adjust the time and voltage scales on the function generator until you can get a good picture of the step response and then use the *Run/Stop* or *Single* scope buttons to capture this response. Measure the period, $T_{res}$, of the step response's oscillations, i.e., $2\pi/\omega_{res}$ and the amount of time

$$\tau_{50\%} = 0.693\frac{2L}{R} \tag{6.0.5}$$

it takes for the amplitude of the damped sinusoidal term to decay in magnitude to 50%. Place these measured values, along with the computed values of $f_{res}$, $R_{ant}$, and $C$, in the Table 6.1 below. Repeat the procedure when the capacitor is half closed and fully open (no overlap of plates). Note that the $R$ value which appears in Eqs. (6.0.1)-(6.0.5) is $R_{ant}+50\,\Omega$, where the 50 $\Omega$ corresponds to the Thevenin equivalent output impedance of the function generator and $L = 960\ \mu$H.

Table 6.1: RLC Time Response and Calculations

| Capacitor | Measured $T_{res}$ ($\mu$s) | Measured $\tau_{50\%}$ ($\mu$s) | $f_{res}$ (kHz) | $R_{ant}$ ($\Omega$) | $C$ ($\mu$F) |
|---|---|---|---|---|---|
| Fully closed | | | | | |
| Half closed | | | | | |
| Fully open | | | | | |

## In-Lab/Post-Lab Problem 8:

(a) Leave the generator connected to points A and B of the RLC circuit shown in Fig. 6.0.1 and the scope probe connected across the variable capacitor to measure $V_{out}$. With the variable capacitor half-closed, measure the frequency response function, i.e. $V_{out}(j\omega)/$(function generator p-p voltage setting). From your data compute the resonant frequency, $f_{res}$, and the 3 dB bandwidth, $BW_{3\,\text{dB}}$ of the resonant response.

(b) Recall (Pre-Lab problem 1) that the frequency response function can be expressed in the following form

$$H(j\omega) = \frac{1}{a_1s^2 + a_2s + 1} \tag{6.0.6}$$

where $s = j\omega$. Express the constants $a_1$ and $a_2$ in terms of $R_{ant}$, $L$, and $C$.

(c) Use your measured data from part (a) to compute $R_{ant}$ and $C$ (see Eqs. (2.2.4)-(2.2.6) in Pre-Lab Section 2.2.2 and recall that $R = R_{ant} + 50\,\Omega$ and $L = 960\,\mu\text{H}$).

(d) Using the values of $R_{ant}$ and $C$ computed in part (c), plot the frequency response function together with the measured data collected in part (a).