

AM Demodulator for Ultrasonic Receiver

In this lab you will construct a demodulator for a 40kHz amplitude-modulated (AM) carrier. This circuit will be used in conjunction with an ultrasonic transducer in Lab #4 to receive and demodulate an incoming signal, which will then be fed into the audio amplifier and speaker driver that you constructed in Lab #2.

There are several things you can learn in this lab if you pay attention. By studying this document and experimenting with the components and circuits in the lab, try to understand the following:

- Basics of AM signals and demodulation
- “Superdiode” rectifier using op-amps
- Design of 1st- and 2nd-order active filters
- Design considerations involving attention to input/output impedances when cascading building blocks

As always, try to understand the role of each component, and how the choice of component value may influence the operation of the circuit. Please tinker with component values: that is an especially valuable way to learn. Ask yourself questions such as: Why is this resistor here? Why does it have this resistance value? Why is this blocking capacitor 0.1 μ F? It is only when you can answer such questions that you will truly understand the labs and progress towards designing your own circuits.

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Pre-Lab Preparation

Read through the lab experiment and data sheets to familiarize yourself with the components and assembly sequence. Bring your solderless breadboard, tools, wire jumpers, audio-amplifier and power supply from labs 1-2.

Optional: simulate the demodulator using MultiSim or Circuit Maker™ (circuit files available on the course web site).

Required Equipment List

Solderless breadboard and Wire jumper kit
Soldering iron and solder
Bench Function generator, power supply, and oscilloscope

Schedule for Lab #3

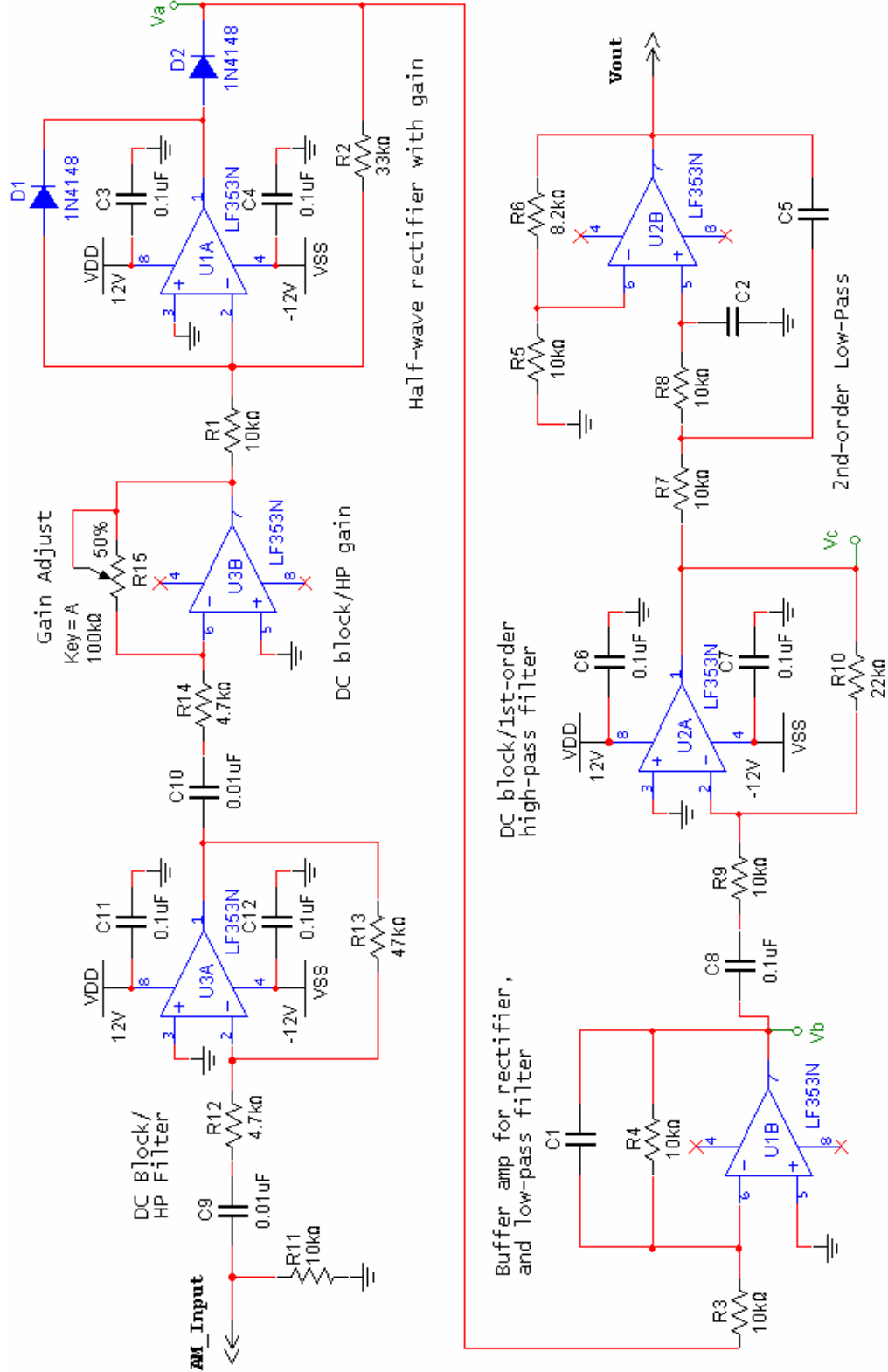
To stay on schedule, you must complete the entire lab in two lab sessions.

Also: double check your kit against the parts list. If you are missing parts, contact the ECE Shop to remedy the situation quickly.

Parts List

Qty	Description	Circuit
3	LF353 Dual Wide-band JFET Op-amp	
3	8-pin low-profile IC socket	
1	4.5" x 2.5" Vectorboard	
2	1N4148 small-signal Silicon diode	D1-2
3	0.001uF capacitor (CKO5 low-volt. Ceramic)	C1-2,C5
3	0.0022uF capacitor (CKO5 low-volt. Ceramic)	C1-2,C5
3	0.0033uF capacitor (CKO5 low-volt. Ceramic)	C1-2,C5
3	0.0047uF capacitor (CKO5 low-volt. Ceramic)	C1-2,C5
2	0.01uF capacitor (CKO5 low-voltage ceramic)	C9-10
8	0.1uF capacitor (CKO5 low-voltage ceramic)	C3-4,C6-8,C11-12
2	4.7kOhm 1/4W	R12,R14
1	8.2kOhm 1/4W	R6
10	10kOhm 1/4W	R1,R3-5,R7-9,R11
2	22kOhm 1/4W	R10
2	33kOhm 1/4W	R2
2	47kOhm 1/4W	R13
1	100K trimpot	R15
1	Stereo Audio jack	
7	flea clips	

Schematics for Lab #3



Schematic for the AM demodulator.

Basics of Amplitude Modulation

Information Transmission

Human speech and music are the original and arguably most important form of “wireless” communication. Although it is conceptually easy to understand the basic operation of the transmitter (vocal cords) and receiver (ear), and the propagation of acoustic waves (vibrating air molecules) between the speaker and listener, it is surprisingly difficult to describe the information content of speech. For example, if we monitor the electrical output of a microphone while someone is speaking into it, the waveforms we observe are complicated and unpredictable. Even if we arrange for each speaker to say exactly the same words, and thus communicate exactly the same *information* across the communication “channel”, the electric signals will differ significantly due to variations in pitch, timbre, and accent or articulation patterns of the different speakers. The relationship between the signal and the information content is obviously complicated, and our brains’ ability to decode these signals truly remarkable.

Fortunately we do not need to understand this relationship well in order to merely transmit the information in a voice or other audio signal. All we need to recognize is that the signals are *band-limited*—that is, they consist largely of a finite range of frequencies or “spectral components”. After analyzing the vocal patterns of many different speakers, and the influence of various electrical filters on the electrical reproduction of their voices, we would conclude that a limited range of frequencies from around 200Hz to about 3-4 kHz is required to communicate intelligible speech. High quality music transmission may require a wider range of frequencies, from 50Hz through 16-20kHz in order to accurately reproduce the more complex acoustical characteristics of musical instruments such as violins and horns, sounds that are rich in spectral content. We can generalize these ideas to any signal we wish to transmit from one point to another, such as a TV signal or a wireless computer data link: each such signal will have a characteristic band of frequencies, or bandwidth, that is required for transmitting the full information content of the signal.

Why modulate?

Modulation is the process of superimposing the desired band of frequencies onto another band of frequencies, with minimal distortion. It proves advantageous to modulate for either or both of the following reasons: (1) to take advantage of the superior propagation or radiation characteristics of high frequency acoustic or electromagnetic waves, or (2) to transmit multiple information channels or wide-band signals simultaneously from one point to another without interference or dispersion. Let’s consider these points briefly.

In order to efficiently radiate an acoustic or electromagnetic wave, we need a radiator (loudspeaker, ultrasonic transducer, or antenna) that is comparable in size to the largest wavelength being transmitted. This is a fundamental property of all types of waves. The wavelength λ is related to the frequency f by the fundamental relation $\lambda = v / f$, where v is the wave velocity. At audio frequencies the acoustic wavelength is reasonably small, typical of most audio speaker systems you are familiar with. But electromagnetic waves at audio frequencies have enormous wavelengths; at 3kHz, the wavelength is 100 km! So it is

impractical to transmit electromagnetic waves at such low frequencies. On the other hand, electromagnetic waves are generally more desirable than acoustic waves for long-distance communication in air, since acoustic waves are more strongly attenuated than electromagnetic waves in air (the opposite is true for undersea communication).

So, in order to take advantage of improved propagation characteristics of electromagnetic waves but keep the antennas to a reasonable size, we need to translate our information signal to higher frequencies during transmission. The high-frequency signal effectively “carries” our information from the transmitter to the receiver.

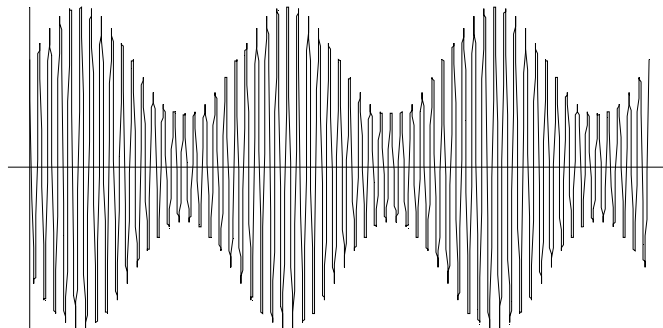
Another great advantage in moving to higher frequencies is that it becomes somewhat easier to cope with wideband signals. The transmitting and receiving antenna will have a finite bandwidth, which is related to the physical structure and also the impedance matching circuit to which it is connected. Typically a bandwidth of 5-10% of the carrier frequency is simple to achieve with a reactive matching network. So moving to higher carrier frequencies makes it easier to realize a given bandwidth. For example, a point-to-point wireless link operating at 24GHz using simple antennas with a 5% bandwidth corresponds to an available information bandwidth of 1.4GHz, enough to support a large number of voice, video, and data channels. Now you can see why people get so excited about fiber-optic systems; the carrier frequency is on the order of 10^{14} Hz, so the intrinsic capacity of the fiber as an information conduit is enormous.

Amplitude Modulation (AM)

So how do we superimpose our information onto a high-frequency carrier? There are many possibilities. One of the easiest to understand and implement is amplitude modulation (AM). In this scheme, the amplitude of the carrier wave is caused to vary in the same manner as the signal being transmitted. If our information-bearing signal is represented as $v(t)$, and the carrier signal is represented as $\cos \omega_c t$, then the AM signal is given by

$$f_{AM}(t) = (1 + m v(t)) \cos \omega_c t$$

where m is the so-called **modulation index**, $0 < m \leq 1$. The figure below shows an AM modulated signal with $v(t) = \sin(\omega_c t / 20)$ and $m = 0.5$.

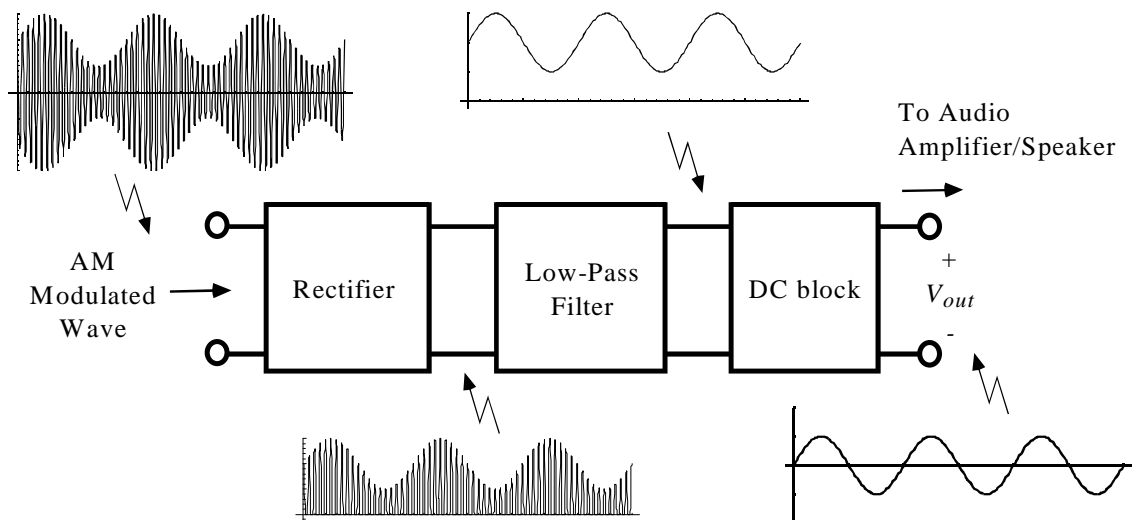


Amplitude modulated sine wave (sinusoidal modulation) with $m = 0.5$.

The information is therefore contained in the **envelope** of the waveform. In order for this scheme to work well, the carrier frequency must be significantly higher than the highest frequency of interest in the desired information-bearing signal.

AM Demodulation Circuits

By far the most common way to demodulate an AM signal is to rectify and filter the modulated signal as shown in the figure below. This technique has much in common with the linear power supply circuit we developed in Lab #1.



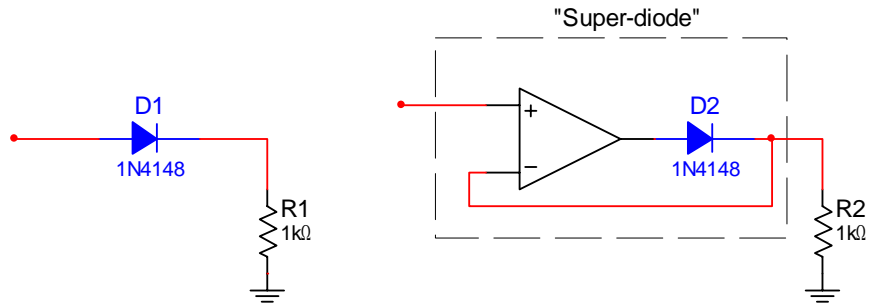
Block diagram of an AM demodulator.

The basic operation is as follows: after rectification, the signal consists of positive pulses of varying strength at the carrier frequency. If we add a filter with an RC time constant that is slow compared with the carrier period but fast compared with the information signal, then the carrier oscillation will be “smoothed out” leaving only the desired envelope. In other words, we should design the filter to strongly reject the high-frequency carrier component of the rectified signal. The resulting waveform will be the desired signal, level shifted to an average DC value corresponding to the carrier amplitude. Since this amplitude will vary depending on the distance between the transmitter and receiver, it is desirable to eliminate this DC component using a DC block, which could be a capacitively-coupled gain stage, or active high-pass filter.

Since the received signal is often very weak, we must also pay attention to the design of the rectifier. Simply using a diode rectifier will not work well if the input signal is on the order of the turn-on voltage (0.7 V). For this reason we will use a *precision rectifier* circuit, constructed using a so-called “superdiode”, which combines an op-amp with a rectifier diode to make a nearly ideal rectifier. We will then use a third-order low-pass filter to eliminate any remnant of the carrier frequency, and a 1st-order high-pass stage for DC blocking and interstage buffering.

“Superdiode”

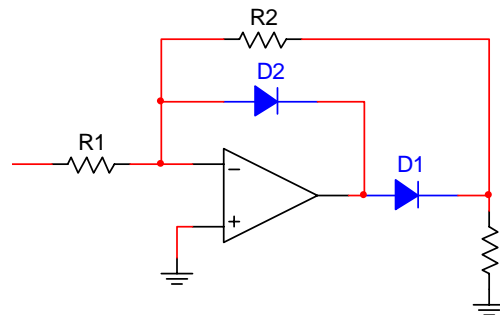
It is easy to construct a rectifier circuit from diodes. A simple half-wave rectifier is shown below. On positive voltage swings the diode conducts and a voltage is developed across the resistor. On negative swings, the diode turns off and the output voltage is zero (no current through the resistor). For large AC signals this circuit works fine, but for small AC signals (smaller than the diode turn-on voltage) we have a problem.



Diode half-wave rectifier circuit, and same circuit using a superdiode.

The basic idea behind the superdiode is to use the high-gain of an op-amp to mask the finite turn-on voltage (and other nonlinearities) of the diode. This is done by placing it in the negative feedback path as shown. Any positive voltage at the op-amp “+” terminal is now sufficient to turn on the diode, and the negative feedback regulates the current through the load resistor to maintain an output voltage equal to the input voltage for these positive input voltage. You may recognize that the circuit is in fact just a unity-gain buffer for positive signals. For negative signals, the output goes negative, and the diode turns off. Because of the high open-loop gain of the op-amp, the circuit operates as a perfect switch for even very small voltages, hence the term “superdiode”.

There are a couple of practical drawbacks to the simple superdiode as shown above. For negative inputs, the output of the op-amp saturates at the negative supply rail. The diode turns off as we want, but now there is no feedback, so the entire input voltage appears across the op-amp terminals, possibly damaging the circuit. Saturating the op-amp like this also has adverse consequences for operating speed. Fortunately there is a simple solution: all we need to do is add a second diode to conduct around the op-amp during the off-cycle. The figure at right shows one useful configuration for a half-wave rectifier, with a couple of resistors added for gain. The superdiode concept can also be extended to implement a full-wave rectifier using an extra op-amp and diode.



Addition of protection diode D2 improves the performance of the rectifier during the off-cycle.

One last comment: the load resistor in the circuits above is rather important. You can appreciate this by considering that a small current must flow through the rectifier diode in the on-state, and this current has to have somewhere to go!

In-Lab Procedure

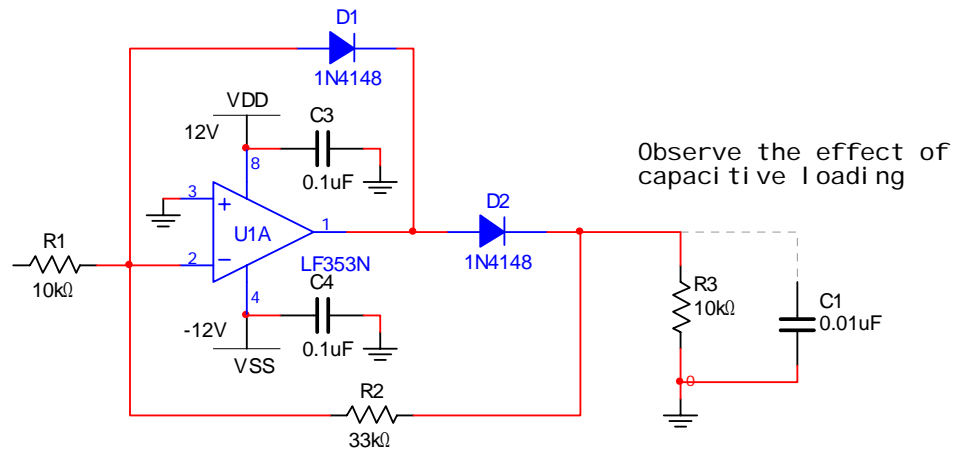
Follow the instructions below **CAREFULLY**. Failure to do so could result in serious damage to the lab equipment, destruction of parts, and possible injury to you and your lab partner.

- Each step begins with a check box like the one at the left. When you complete a step, check the associated box. At the end of this document is a **LAB RECORD** in which you will record key observations and results from the experiment. When you are finished with the lab, you must demonstrate a working circuit and a completed lab record, and get this signed and certified by one of the lab TAs.

Step 1 – Superdiode Rectifier Stage

Now that you are all experts in circuit prototyping, the procedure for this lab needs very little explanation. The important thing is to take the time to understand the role of each component and the design methodology. Feel free to tinker with component values to improve the circuit.

- First add your op-amps onto your breadboard and provide power connections and bias decoupling capacitors for each chip. Then construct the superdiode rectifier stage as shown below.



Precision rectifier (bypass capacitors not shown).

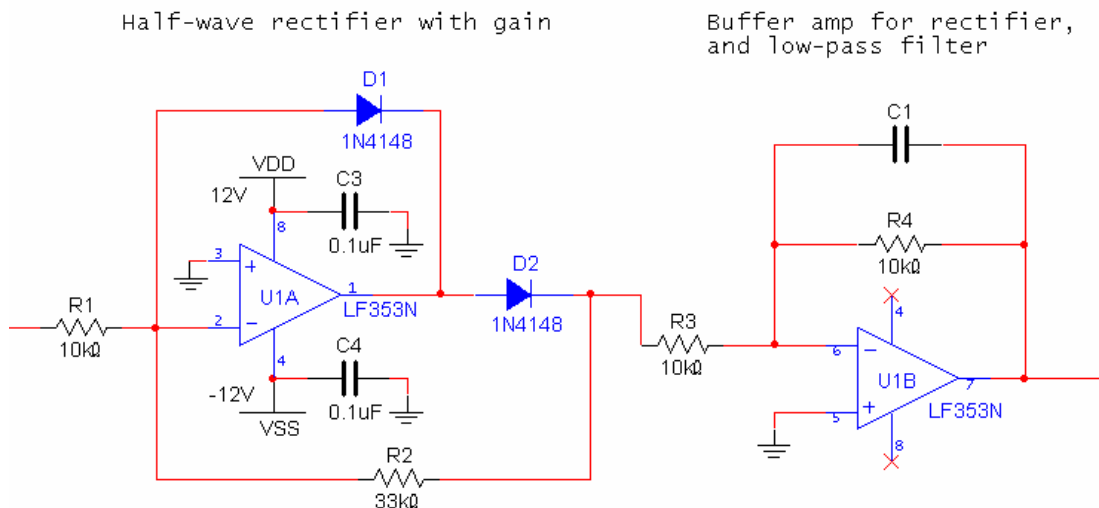
- Unfortunately your bench function generator does not easily support AM signal generation, so we will do much of the preliminary testing of the circuit with an unmodulated sinewave. Drive the circuit using a 40kHz signal with a 0.1V amplitude and record the output waveforms in the Lab Record.
- Try disconnecting resistor R3 and observe the output waveform. What can you conclude?
- Add a small capacitor (say 0.01μF) in parallel with R3 and observe the change in output waveform.

- Answer the remaining questions in the lab record for this stage. Consult your class notes and handouts for help.

Step 2 – Low-pass Buffer

Ideally we would follow the rectifier with a DC-blocking stage before further amplification and low-pass filtering, but as we saw in Step 1, the rectifier needs to see a resistive load with very little capacitance in order to function properly. So first we'll add a buffer to present a resistive input impedance to the rectifier stage and a low output impedance for subsequent active filter stages. Adding a capacitor C1 turns this stage into a first-order low-pass filter, which helps eliminate some of the carrier component. In Lab #4 you may find it useful or necessary to adjust the values of R2 and R4, but using the values shown in the schematic is fine for now.

- Construct the low-pass buffer stage as shown, and test under the conditions listed in the lab record. Choose C1 to set a cutoff frequency around 5-7kHz so that we can pass the desired audio frequencies and filter out some of the 40kHz carrier.



- Answer the remaining questions in the lab record for this stage. Consult your class notes and handouts for help.

Step 3 – DC Blocking Stage

The simplest way to accomplish a DC block is to simply insert a large capacitor in series with the signal path. However, we must be careful when doing this between active filter stages, since most filters need to be driven from a low-impedance source. In addition, the capacitor will add a pole in the response function, so we need to choose it carefully. In our circuit the DC block is implemented as a simple first-order high-pass inverting amplifier stage. A higher-order filter is not needed here.

- Construct the high-pass buffer stage next, and test under the conditions listed in the lab record. Refer to the schematic on page 1.
- Answer the remaining questions in the lab record for this stage. Consult your class notes and handouts for help.

Step 4 – 2nd order Low-pass

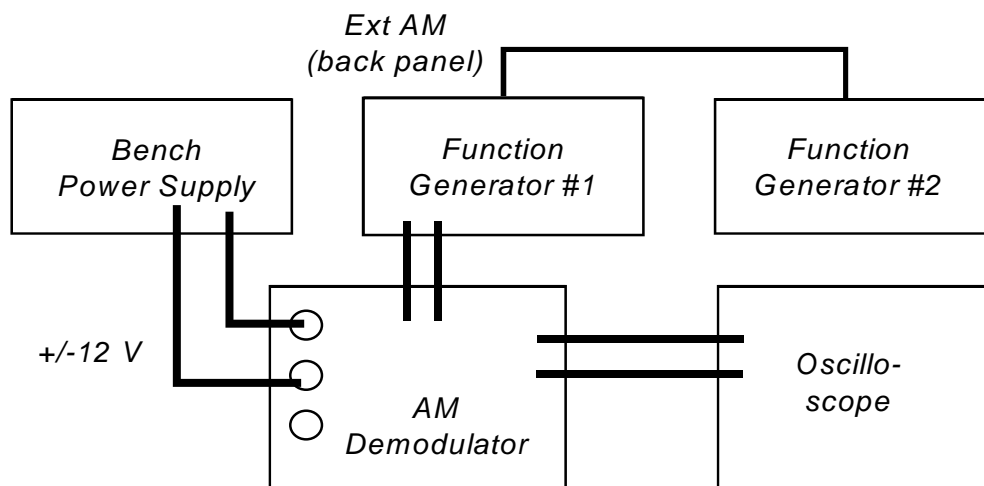
The last component in the demodulator chain is a low-pass filter to eliminate the residual carrier frequency components in the waveform. A second-order Sallen-key filter was selected for this purpose, but you will need to choose the capacitor values.

- Construct the 2nd-order low-pass stage next. Refer to the master schematic. You should choose the capacitors such that the two poles are the same or close to the pole you chose in the filter of Step 2.
- Answer the remaining questions in the lab record for this step. Consult your class notes and handouts for help.

Step 5 – Complete Demodulator Circuit

The last step is to test the operation of the demodulator circuit using a true AM input signal. The TA will set up one bench on the lab specifically for this purpose, as shown below. An AM signal can be generated by using one of the bench function generators (#1) as the carrier frequency, and another (#2) as the modulation source, which is coupled into the “External AM” connector located at the back of the function generator #1.

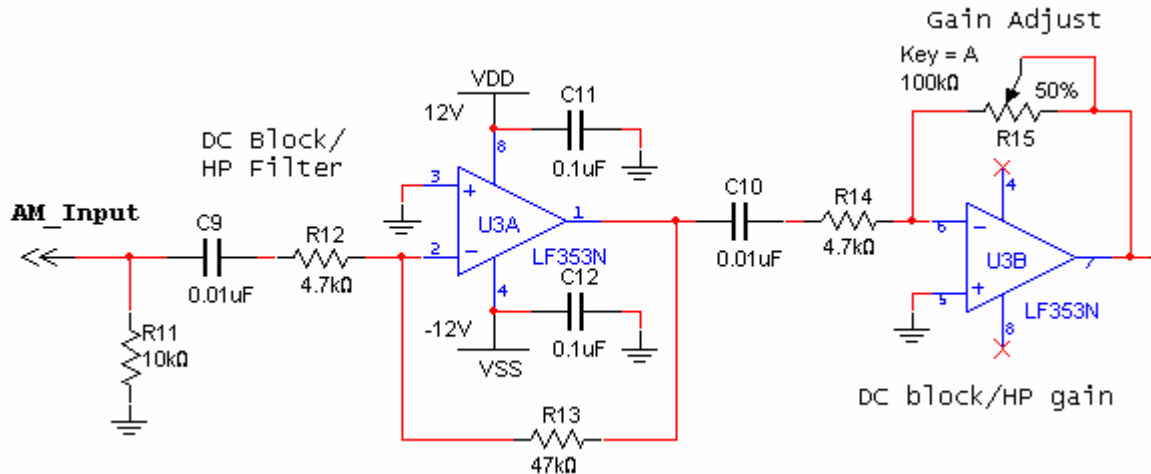
- With the TA’s help, test your demodulator circuit using the AM setup below, and answer questions in the Lab record.



Referring to the schematic, you’ll see we aren’t quite done yet. There are a couple of AC-coupled gain blocks that feed the rectifier circuit. These will be needed in the final

transceiver system to amplify the very weak signal detected by the ultrasonic transducer. These stages have a high-gain, so it is important to AC-couple them so that we don't multiply any DC offsets in the system. You will notice that the coupling capacitors in this case are rather small; find the two poles associated with this circuit. Note that the desired signal that we want to receive is in the range of 38-42kHz.

- Add the gain stages to your circuit as shown below.



Pre-amplifier stage for the demodulator circuit

Step 6 – Hardwire the Receiver Circuit

- Transfer your completed design to vectorboard. Your board should have external connections for power, an AM-modulated signal, and an audio output. Since we will eventually use our audio amplifier circuit, use the audio jack in your kit to provide an audio output for connection to the amplifier. When finished, verify the functionality of your circuit using the function-generator, Lab #1 power supply, and Lab #2 amplifier.

Congratulations: you now have an ultrasonic demodulator circuit!

Possible Improvements

It's a little premature to discuss improvements until we actually see the circuit in operation in the complete communications system. But a couple of obvious possibilities are as follows: we could implement a full-wave rectifier instead of the half-wave rectifier, which would simplify the subsequent filtering somewhat; we also anticipate that the ultrasonic transducers will have a certain frequency response, in particular a finite bandwidth, so it would be desirable if the receiver circuit could compensate for this somehow. This could be accomplished by shaping the frequency response of the receiver such that the product of the transducer response and receiver response is a constant.

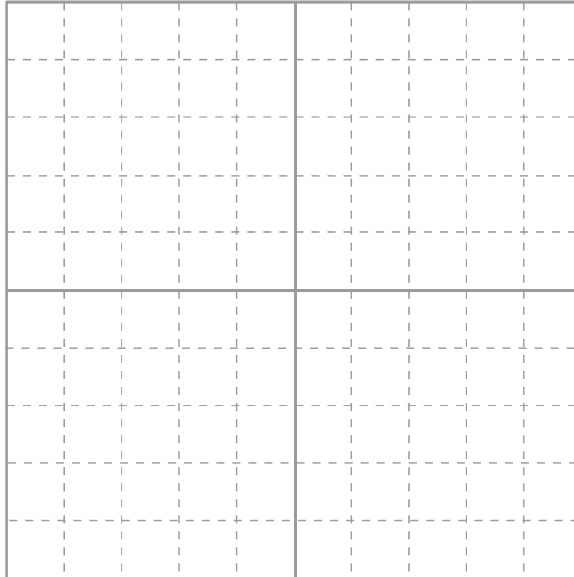
Lab 3 Record

Section _____

Names: _____

Step 1 – Superdiode Rectifier

Record the waveforms at the output of the rectifier for a 0.1 V, 40kHz sinewave input:



What is the input impedance of the rectifier stage?: _____ Ω

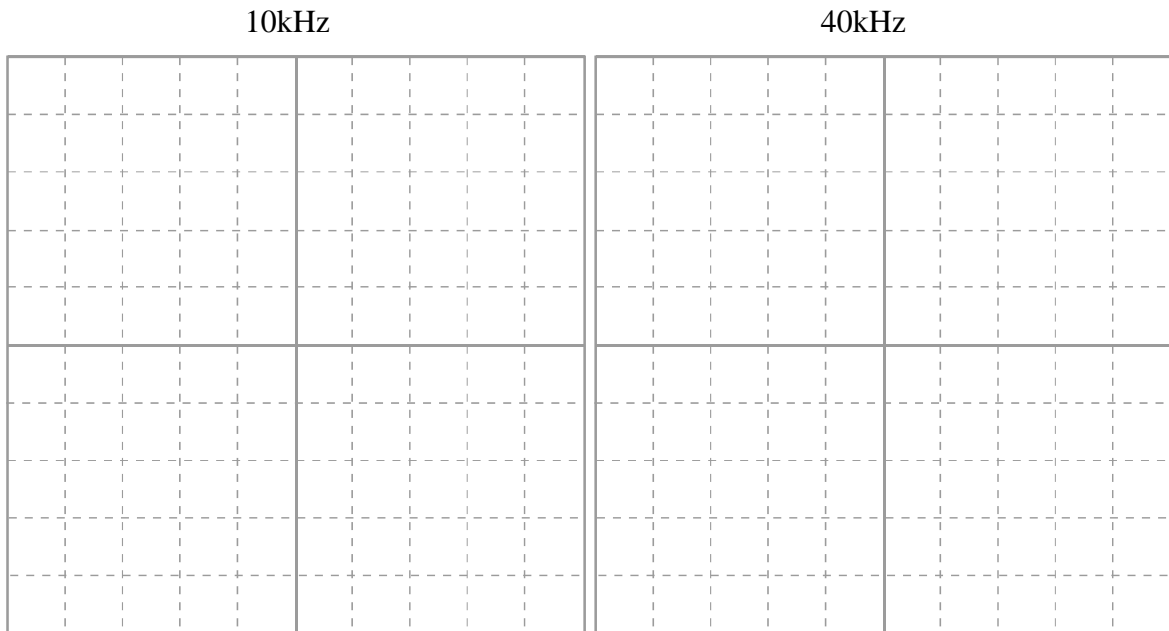
Describe the function of diode D1:

What is the theoretical voltage gain of this rectifier stage? _____

What is the measured voltage gain of this rectifier stage? _____

Step 2 – Low-Pass Buffer

Record the output waveform of the low-pass buffer (terminal Vb) for a 0.1V sinewave at the input of the rectifier for the following two frequencies:



What is the input impedance of the low-pass buffer stage?: _____ Ω

What capacitance value did you choose for C1?: _____ μF

What is the theoretical cutoff frequency for your design?: _____ kHz

What is the theoretical voltage gain in the passband? _____

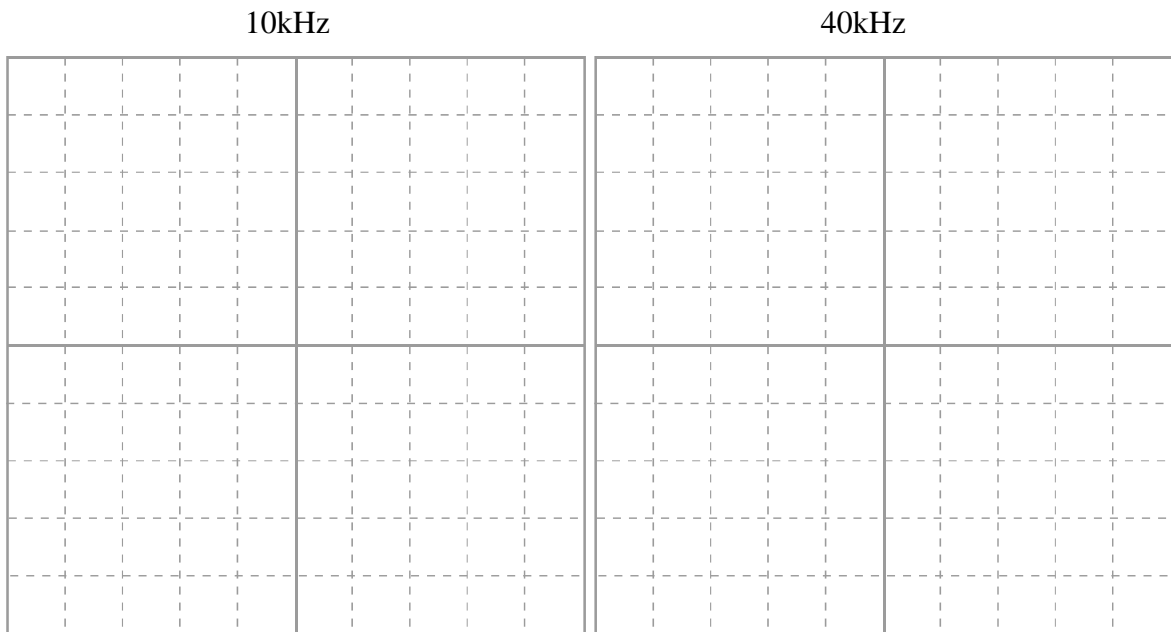
What is the theoretical roll-off outside of the passband? _____ dB/decade

Step 3 – DC blocking buffer

What is the theoretical cutoff frequency of this stage? _____

Could we interchange the positions of the low-pass buffer and DC blocking stage? Defend your answer.

Record the output waveform of this stage (terminal Vc) for a 0.1V sinewave at the input of the rectifier for the following two frequencies:



Step 4 – 2nd order low-pass

What is the input impedance of this stage?: _____ Ω

What capacitance value did you choose for C2 & C5?: _____ μF

What is the theoretical cutoff frequency for your design?: _____ kHz

What is the theoretical voltage gain in the passband? _____

What is the theoretical roll-off outside of the passband? _____ dB/decade

Could we interchange the positions of this low-pass stage and the DC blocking stage? Defend your answer.

Step 5 – Complete Demodulator

Record the input and output waveforms of your demodulator for an AM input signal as described in the text:

Input Signal				Output (Vout)			

Step 6 – Hardwired circuit

Check this box when finished with Step 6 and the circuit is functioning.

Circuit hardwired and functioning: Yes []

TA Certification: _____

Date: _____