UNIVERSITY OF CALIFORNIA, DAVIS
College of Engineering
Department of Electrical and Computer Engineering

EEC 112 (Communication Electronics) Laboratory Manual

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I. OBJECTIVES

In this laboratory, you will design, build, and test AM and FM transmitters and receivers. The objectives of the lab are:

1. to reinforce the lecture material in this course,
2. to teach the use of basic electronics lab equipment,
3. and to develop good laboratory practice.

II. LAB NOTEBOOK

A key part of good laboratory practice is to maintain a lab notebook. All your pre-lab calculations, lab notes, data, and reports should be kept in a bound lab notebook. Lab reports need not repeat information that is already in this lab manual. However, your lab notebook and manual together should contain enough information to repeat the experiments. For example, after completing a pre-lab assignment, you may find that your calculated component values do not produce optimum measured results. Your lab notebook should summarize your tests with other component values. Most of your lab time should be spent reading the experiment, doing the pre-lab assignment, and doing the experiment instead of writing a report. Each student should maintain a separate lab notebook, prepared completely by the student himself/herself.

III. PROTOBOARDS

Although the performance of the circuits described in this manual could be improved by using printed-circuit boards with a ground plane, all the circuits for these experiments will be built on protoboards to simplify construction and revision of the circuits. Each group will need at least one protoboard, and two protoboards per group would be helpful. For example, using two protoboards would allow each group to test corresponding transmitters and receivers together instead of only testing each separately.

If the protoboard you have been using in other classes is wearing out, you should buy a new one for this class. The circuits that you will build in this laboratory are complicated enough that debugging will be challenging even with a new protoboard. Old protoboards that do not make reliable connections to **every** component will greatly increase the difficulty in debugging.

Even with new protoboards, the characteristics of the protoboard will affect the measured results for the circuits that you construct in this class. In particular, protoboards have a large parasitic capacitance (about 5 pF) from any one row of pins to the next. At 100 MHz, 5 pF corresponds to a capacitive reactance of only about 300 Ω. Therefore, the isolation between adjacent "unconnected" rails may be poor. Also, because protoboards do not usually use a low-impedance ground plane, the inductance in the ground connection may be high. Therefore, circuits may interact through the power and ground rails in ways that would not be predicted when ideal power-supply and ground connections are assumed. For example, multi-stage high-gain amplifiers sharing the same power-supply and ground rails may oscillate because of feedback through the supply or ground connections.

IV. TOOLS

In addition to protoboards, each lab group will need a pair of needle-nose pliers and wire cutters/strippers. Although these tools are not required for other lab courses, they are required here to help you build your circuits in as small a form as possible. This is important because several of these experiments operate at frequencies where parasitic inductances and capacitances from long component leads may cause performance limitations. Problems from these parasitics will be reduced by minimizing lead lengths with the use of these tools. On the other hand, the component leads need not be so short that probing the circuit to make measurements is difficult.

V. EQUIPMENT

1. General

   Please do not remove any equipment from the lab room, including probes and cables. However, you are welcome to take your parts with you out of the lab room.

2. Oscilloscope

   a. Each bench has an oscilloscope with a 50-MHz bandwidth limit. Most of the benches also have an oscilloscope with a 100-MHz bandwidth limit. The 100 MHz bandwidth will be required in some cases such as in Experiment #2, where the goal is to build an FM transmitter that operates between 88 MHz and 108 MHz.

   b. While signals above 100 MHz can be examined, some attenuation should be expected.

   c. When you want to observe the phase relationship between two signals (such as in the phase-locked loop in Experiment #5), display both simultaneously on the oscilloscope and trigger on channel 1 or channel 2. Do not trigger on "vert mode" when you want to see the phase difference between two signals.

3. Probes

   The lab has 100-MHz "10X" oscilloscope probes available for your use. These probes attenuate the input signal by a factor of 10. This attenuation increases the input impedance of the probe. As a result, the loading caused by these probes on a circuit under test at high frequencies is much less than the "1X" probes you have used in other labs, which consist of coaxial wire with alligator clips.

4. Power Supply

   The experiments use a +12-Volt power supply. The "COM" terminal on the supply should be viewed as the "negative" side of the power supply.

5. Arbitrary-Waveform Generator

   a. This arbitrary-waveform generator has many built-in waveforms, including sine (up to 20 MHz), square (up to 10 MHz), and triangle (up to 200 kHz) waves. Also, it can produce several kinds of modulations, including amplitude, frequency, and phase.

   b. This generator has two output channels, allowing it to produce two independent outputs at the same time.

6. Spectrum Analyzer
   a. Since the lab room does not have a spectrum analyzer for each bench, use of the spectrum analyzers is not required in any of the experiments. However, use of the spectrum analyzers is highly recommended, especially to observe the spectra of both amplitude- and frequency-modulated signals.
   b. The lowest frequency that the spectrum analyzer will properly display is 9 kHz. Therefore, it cannot be used to display the spectrum of the unmodulated voice-band signals you will use in this course.

VI. DEBUGGING TIPS

1. Try to build your circuits linearly so that the entire circuit runs down one power/ground strip.
2. Do not assume that a component has the value indicated on the bin from which it was selected. Learn to read and measure the component values directly.
3. Try to build your circuits so that the correspondence between the schematic and the layout is easy to see. This process will help you separate components that are properly connected from those that are not. Simplicity is of the essence here because simple layouts reduce the time required for checking.
4. When a circuit does not work as expected, the process of finding and fixing the problem can be expressed as "divide and conquer." This expression means that you separate the parts of the circuit that work correctly from those that do not. To do this separation, you must know what to expect at the output of each circuit and sub-circuit that you are building. This knowledge requires thinking about and possibly simulating the circuit before coming to lab. The basic idea is to start at the output and work toward the input until you find something that works correctly. Alternatively, you can start at the input and work toward the output until you find something that works incorrectly. Then you try to narrow down the exact point at which the circuit transitions from working correctly to incorrectly. This process can be simple or difficult, depending on the problem.
5. In many cases, checking the d.c. biasing is a good way to determine whether a circuit is correctly connected and operating properly.
6. Do not assume that the output of an instrument is correctly indicated on the instrument's panel. Always check the output with an oscilloscope or other measuring device.
7. If your power-supply voltage is not constant, use extra bypass capacitors. In commercial products, each supply is usually bypassed by more than one capacitor. On the one hand, an electrolytic capacitor of about 10 μF is often used to filter low-frequency noise from each supply. Therefore, it can be placed anywhere on the supply rail because parasitic inductance in the supply line between the capacitor and the elements connected to the supply is of little consequence at low frequencies. On the other hand, ceramic capacitors of about 0.01 μF or 0.1 μF are often used to filter high-frequency noise from the supply. To minimize the effect of series inductance, the leads of these ceramic capacitors should be minimized, and they should be placed as close as possible to points where the supply voltage is used.

8. When circuits from previous experiments are not in use, disconnect the power supplies from these circuits so they do not interfere with the circuits under test.
9. Occasionally, a component is not functional or does not make proper contact with the protoboard. Since this is rarely a problem, concentrating on other potential problems first is usually a good idea. If you do find a defective component, please throw it away!

VII. DATA SHEETS

The data sheets for some of the integrated circuits can be found on Texas Instruments' world-wide-web (WWW) pages. The table below shows the part numbers, the experiments in which they are used, and the WWW addresses. Printing all the data sheets at one time may save time in the long run.

Part Number	**Experiments**	**Datasheet address on WWW**
LM741	1-2	http://www.ti.com/lit/ds/symlink/lm741.pdf
LM1496	3-5	EEC112 class web page this quarter
CA3086	3-4	EEC112 class web page this quarter
LM386	3-5	http://www.ti.com/lit/ds/symlink/lm386.pdf
LM565	5	EEC112 class web page this quarter

VIII. ACKNOWLEDGMENT

Mehmet Aslan designed, built, and tested the prototypes for Experiments #4 and #5. He also wrote the first draft of the procedures for the same experiments. I am grateful for his help.

Several other students contributed to the development of these labs, including Ara Bicakci, Arne Buck, Adam Eldredge, Ryan Fawkes, and Stephanie Mo. Jonathan Tao found errors in equation (1.3) and the surrounding paragraph. Sajjad Sabbaghi pointed out references to equipment no longer in use. I appreciate these contributions and the support of Barry Vose and Jim Gage in EGS as well as Lance Halsted in ECE.

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UNIVERSITY OF CALIFORNIA, DAVIS
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EEC 112
Experiment #1
AM Transmitter

PARTS LIST

R_5 R_9 R_{10} R_{11}	47 Ω 270 Ω 1 kΩ 39 Ω
L_1	100 µH Epoxy Dipped (ESS #1N100UH, Mouser #43LR104, or equiv.)
L_3	10 mH Molded Plastic (ESS #1N10MH or equiv.)
L_4	10 µH Epoxy Dipped (ESS #1N10UH, Mouser #43LR105, or equiv.)
L_5	1 mH Epoxy Dipped (Mouser #43LR103 or equiv.)
C_4 C_8 C_9 C_{10} C_{11} C_{12} C_{13}	0.01 µF - 0.1 µF 0.01 µF - 0.1 µF 0.01 µF - 0.1 µF 0.01 µF - 0.1 µF 0.01 µF - 0.1 µF 2.2 nF 2.2 nF
Q_1 Q_3 Q_4	2N2222 2N2222 2N2222
Voice-Band Input Voice-Band Amplifier	8-Ω speaker LM741 and Miscellaneous resistors and capacitors

All resistors should be able to dissipate at least 1/4 Watt and all capacitors should be able to withstand at least 20 V.

I. INTRODUCTION

Amplitude modulation (AM) is the process of forcing the amplitude of a high-frequency carrier signal to follow the amplitude of a low-frequency information signal. In the United States, AM is used for radio broadcast from 535 kHz -1605 kHz. Adjacent broadcast channels are separated by at least 10 kHz. Therefore, the maximum frequency of the information signal is 5 kHz. In this experiment, you will design and build a simple AM transmitter with a carrier frequency somewhere in this band so you can listen to your transmission using a standard commercial AM radio receiver. Rules for the intentional radiation of radio frequency energy in this band are published by the Federal Communications Commission (FCC) in the Code of Federal Regulations (CFR), Part 47, Section 15. These rules span 56 pages, and the essence is that your transmitter is not allowed to interfere with other peoples' communications devices, including radios and televisions for example. To conform to these rules, the transmission range of the transmitter described below is extremely limited. If you operate a transmitter outside the laboratory, it is your responsibility to read and abide by these rules. They can be found in the government documents section in the basement of Shields Library.

II. CIRCUIT

Figure 1.1 shows a block diagram of the transmitter.

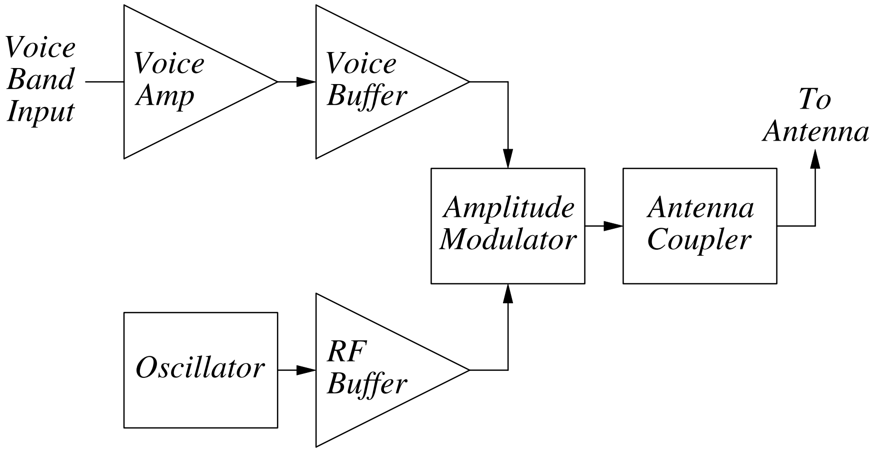

Fig. 1.1: Block Diagram of an AM Transmitter

It consists of a voice-band amplifier, voice-band buffer, oscillator, radio-frequency (RF) buffer, amplitude modulator, and antenna-coupling network. Figure 1.2 shows a schematic of all the circuits except the voice-band amplifier and the oscillator.

The voice-band buffer consists of Q_1, R_5, C_4, and L_1. Transistor Q_1 operates as an emitter follower, which reduces the effect of the loading from the modulator on the voice-band amplifier. The purpose of R_5 is to limit the maximum current that can flow in Q_1. The purpose of L_1 is to allow the low-frequency voice-band signal to control the average voltage from the collector of Q_4 to ground. Also, L_1 and C_4 attenuate the feedthrough of the high-frequency carrier to the voice-band amplifier. A resistor is not required from the emitter of Q_1 to ground because non-zero d.c. current flows through L_1.

The RF buffer consists of Q_3, L_3, C_8, and R_9. Transistor Q_3 also operates as an emitter follower, which reduces the effect of loading from the modulator on the oscillator. Inductor L_3 is a radio-frequency choke (RFC). Together with C_8, it attenuates the feedthrough of the high-frequency carrier to the power-supply lead, reducing accidental RF radiation. (The transmitter should only broadcast from the antenna.)

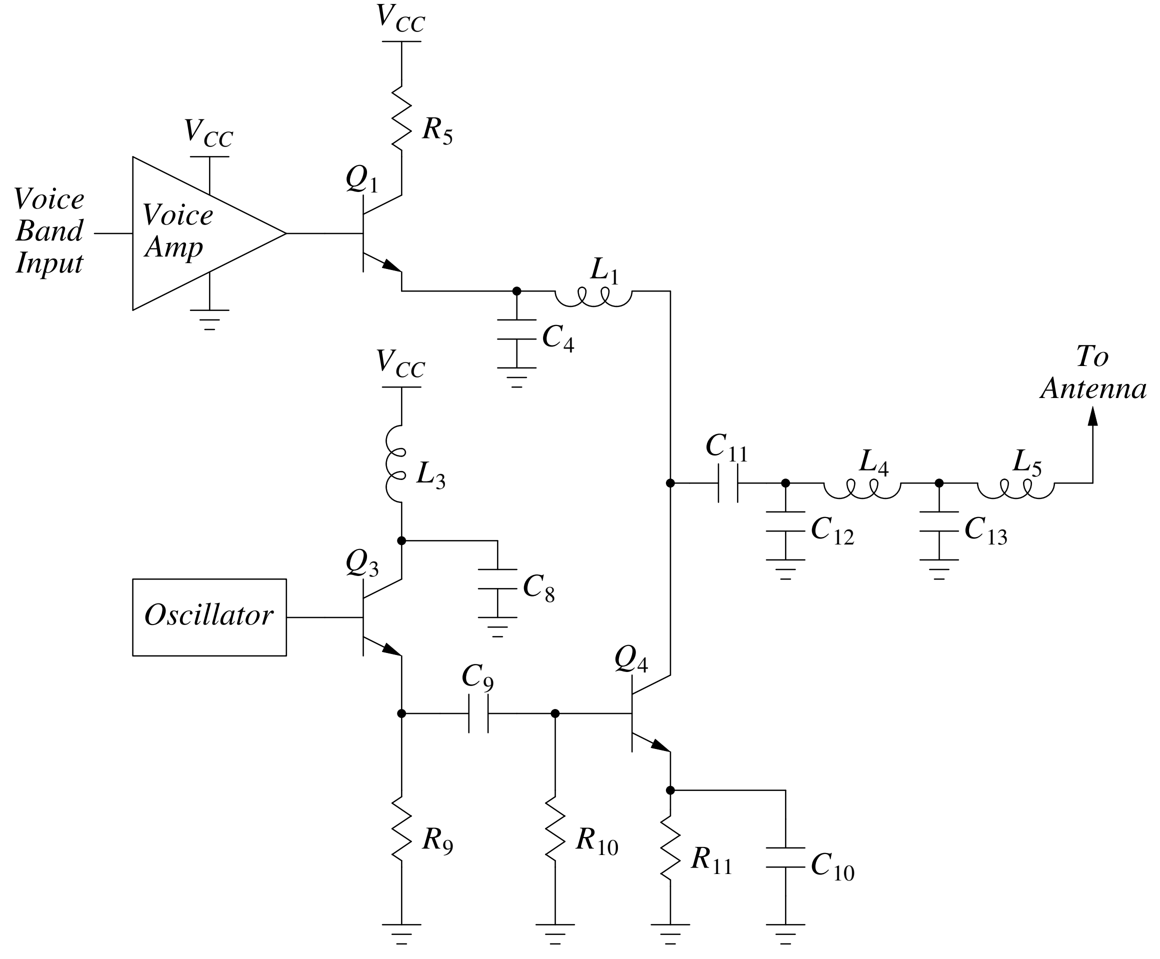

Fig. 1.2: Schematic of an AM Transmitter

In the broadcast AM band, the FCC requires that the antenna and connections must be less than 3 meters long. Therefore, the carrier wavelength is much longer than the antenna length. For example, a 1-MHz carrier has a wavelength of 300 meters. Under these conditions, the antenna can be modeled by a series connection of a resistor and a capacitor. If the Ohmic resistance of the antenna and ground plane is zero, the value of the resistor is the radiation resistance, which models the power transmitted from the antenna to free space. If the antenna is a vertical conductor over a horizontal ground plane, the radiation resistance, R_{rad}, in Ohms is:

$$R_{rad} = 40\pi^2\left(\frac{h}{\lambda}\right)^2, \tag{1.1}$$

where h is the height of the antenna and λ is the wavelength of the carrier [1-3]. In this application, the radiation resistance is very small (0.04Ω for a 3-meter antenna at 1 MHz), which means that such a short antenna radiates little power. Also, the series capacitor in the antenna model represents energy stored in the electric field around the antenna. The capacitance, C_{series}, in picoFarads is:

$$C_{series} = \frac{24.2(h)}{log(2h/d) - 0.7353}, \tag{1.2}$$

where h is the height and d is the diameter in meters [3, 4]. For antennas less than 3 meters long with a diameter of 2.5 mm, the series capacitance is about 9 pF/ meter. In practice, Equations (1.1) and (1.2) are only approximate because of imperfections in the ground plane as well as electromagnetic coupling to objects near the antenna.

The antenna coupler consists of $C_{11} - C_{13}$ and $L_4 - L_5$. Inductor L_5 acts as a loading coil. Its purpose is to resonate with the series capacitance in the antenna model so that the antenna appears resistive at the carrier frequency. A 3-meter antenna transmitting at 1 MHz is assumed in the parts list. Since Equation (1.2) is only approximate, however, the optimum value of L_5 is difficult to predict analytically. The purpose of C_{11} is to block d.c. signals. Capacitors $C_{12} - C_{13}$ and inductor L_4 together form a matching network that is intended to increase the power transfer from the modulator to the antenna. The matching network acts as a tuned circuit. Straightforward linear analysis can be used to show that the parallel impedance of these three elements is:

$$Z = \frac{1 + s^2 L_4 C_{13}}{s(C_{12} + C_{13})(1 + s^2 L_4 C_{EQ})} \tag{1.3}$$

where $C_{EQ} = C_{12}C_{13}/(C_{12} + C_{13})$. Therefore, if we view the input from Q_4 as a current, and if we ignore C_{11}, L_5, the antenna impedance, and parasitic impedances, Eq. (1.3) shows that the maximum antenna output occurs at $\omega = 1/\sqrt{L_4 C_{EQ}}$, which is about $2\pi(1.5)$ Mr/s or 1.5 MHz with the element values given in the parts list. The matching also attenuates the output of the modulator at harmonics of the carrier frequency. This is important here because another FCC requirement in this band is that emissions above 1.7 MHz must be attenuated so that they are at least 20 dB below the carrier.

The modulator consists of C_9, R_{10}, Q_4, R_{11}, and C_{10}. Because C_9 blocks d.c. signals, the d.c. voltage from the base of Q_4 to ground is approximately 0 V. Therefore, Q_4 is biased in the cutoff region and acts as a Class-C amplifier. That is, Q_4 remains off for most of the carrier period and turns on only for a short time each period when the oscillator output is positive enough to forward bias the base-emitter junction of Q_4. When Q_4 turns on, it pulls a pulse of current from its collector toward its emitter until it saturates. The current pulses occur at the carrier frequency. Because L_1 is selected to provide a higher impedance than the antenna coupler at the carrier frequency, the current pulse comes primarily from C_{12} in the antenna coupler. Therefore, the current pulses increase the amplitude of the oscillation in the antenna coupler. Since the pulses occur only when Q_4 is not saturated, and since the average voltage from the collector of Q_4 to ground is controlled by the output of the voice-band buffer, the envelope of the oscillations in the antenna coupler are forced to follow the amplified voice-band input. That is, an AM signal is generated.

III. PRE-LAB ASSIGNMENT

The input to the voice-band amplifier should come from an ordinary 8-Ω speaker, acting as a microphone. Using a microphone input, design a voice-band amplifier that provides a gain of about 200 in the band from about 100 Hz to about 4 kHz. You are allowed to use a 741 op amp with $V_{EE} = 0$ along with miscellaneous resistors and capacitors. The data sheet for the LM741 can be found on the world-wide web as indicated in Section VII on or near page 4 of this lab manual. If you use a 741 op amp under these conditions, you should bias the non-inverting input to mid-supply, a.c. couple the input from the speaker, and choose resistor values that eliminate offset arising from non-zero input bias current. The unity-gain bandwidth of the 741 op amp is about 1 MHz. Therefore, the bandwidth with a closed-loop gain of 200 will be about 5 kHz.

IV. EXPERIMENT

For this experiment, you should use V_{CC} = 12 Volts and the first channel of an arbitrary-waveform-generator output as the oscillator unless otherwise stated. Also, the oscillation waveform should be sinusoidal unless otherwise specified. The oscillation frequency should be somewhere in the AM broadcast band. The peak-to-peak amplitude of the oscillator output should be about as large as the power supply.

1. To let you observe the amplitude modulation even when you are not talking into the speaker, you can provide a continuous sinusoidal signal at some voice-band frequency in parallel with the speaker acting as a microphone. This signal can be produced by the second channel in the arbitrary-waveform generator. If the minimum amplitude of this signal overloads the transmitter, a resistive attenuator between the output of the second channel in the arbitrary-waveform generator and the speaker input can be created as described below.
2. Build the transmitter, using a piece of insulated wire no longer than 3 meters as an antenna. If an attenuator between the output of the second channel of the arbitrary-waveform generator and the speaker input is required, adjust the value of the series resistance in the attenuator connected to this channel so that the modulation index with a 100-mVp-p input is about 10%. The speaker itself can act as the shunt resistance in the attenuator. Equation (1.4) defines the modulation index, m,

   $$m = \frac{\max - \min}{\max + \min}, \tag{1.4}$$

   where max and min are the maximum and minimum peak-to-peak amplitudes of the output at the antenna. If you use a standard AM receiver to help test your transmitter, keep the volume low enough so that you do not disturb others in the lab. If a receiver is not available, you can observe the performance of your transmitter using an oscilloscope and a spectrum analyzer. If necessary, adjust the gain in the voice-band amplifier so that input from the speaker is easily observable. Also, please cooperate with others in the lab to avoid transmitting signals that interfere with those transmitted by other groups.
3. After you get the transmitter working, reduce the peak-to-peak amplitude of the oscillator until the transmitter stops working. Record the range of oscillation amplitudes for which the transmitter works. (Limit the maximum peak-to-peak amplitude to be about equal to the power-supply voltage.)
4. Again set the peak-to-peak amplitude of the oscillator output to be about equal to the supply voltage. Set the amplitude of the voice-band input so that modulation index is about 50% for an input frequency of 1 kHz. Sketch the waveform at the antenna output. Measure and record the modulation index for input frequencies of 100 Hz and 4 kHz.
5. Return to an input frequency of 1 kHz. Using the XY mode on an oscilloscope, display the antenna output and the output of the voice-band amplifier for a 100-mVp-p input

from the second channel of the arbitrary-waveform generator. (Many oscilloscopes enter the XY mode when the time base is rotated all the way counter-clockwise.) Increase the output of the second channel of the arbitrary-waveform generator to 600 mVp-p. Sketch the patterns observed. See pages 88-89 in *Communication Circuits: Analysis and Design* by Clarke and Hess to understand the displayed patterns.

6. Measure the power dissipated from the V_{CC} supply.
7. Reduce V_{CC} to the minimum value required to keep the transmitter working and record this value of V_{CC}. Measure the power dissipated from the reduced V_{CC} supply.
8. Return to $V_{CC} = 12$ Volts. Change the waveform at the oscillator output from a sine wave to a square wave. Is a sinusoidal waveform at the oscillator output important?
9. Demonstrate your transmitter to your TA.
10. If time allows, design and build an oscillator for your transmitter. Use the information gathered above to determine the important characteristics of the oscillator output. If possible, determine the range of your transmitter to a standard commercial AM receiver.
11. If possible, keep the transmitter intact so that you can test it with the AM receivers that you will build in Experiments #3 and #5.

V. REPORT

For your report, describe what you expect to observe in each of the parts of the experiment above and explain (where applicable).

VI. REFERENCES

[1] W. H. Hayt, Jr., *Engineering Electromagnetics,* p. 432-436, McGraw-Hill, New York, 1989, Fifth Edition.

[2] S. E. Schwarz, *Electromagnetics for Engineers,* p. 356-359, Saunders, Philadelphia, 1990.

[3] U. L. Rohde and T. T. N. Bucher, *Communications Receivers Principles and Design,* p. 175-177, McGraw-Hill, New York, 1988.

[4] S. A. Schelkunoff and H. T. Friis, *Antennas: Theory and Practice,* Wiley, New York, 1952.

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EEC 112
Experiment #2
FM Transmitter

PARTS LIST

R_1 R_2 R_3	10 kΩ To be determined 220 Ω
L_1	10 mH Molded Plastic (ESS #1N10MH or equiv.)
L_2	0. 1 µH - 0. 2 µH about 6.25 inches of #19 enamel coated magnet wire wound around a standard pencil or Epoxy Dipped Mouser #43LR227 or equiv.
L_3	10 mH Molded Plastic (ESS #1N10MH or equiv.)
C_1 C_2 C_3 C_4	3 pF To be determined To be determined 1 nF
Q_1 Q_2	2N2222 2N2369
Voice-Band Input Voice-Band Amplifier	8-Ω speaker LM741 and Miscellaneous resistors and capacitors

All resistors should be able to dissipate at least 1/4 Watt and all capacitors should be able to withstand at least 20 V.

I. INTRODUCTION

Frequency modulation (FM) is the process of forcing the frequency of a high-frequency carrier signal to follow the amplitude of a low-frequency information signal. In the United States, FM is used for radio broadcast from 88 MHz -108 MHz. Adjacent broadcast channels are separated by at least 200 kHz. The maximum frequency of the information signal is 15 kHz, and the maximum frequency deviation from the carrier frequency is limited to 75 kHz. In this experiment, you will design and build a simple FM transmitter. The goal is to set the carrier frequency between 88 MHz and 108 MHz so you can listen to your transmission using a standard commercial FM radio receiver. Rules for the intentional radiation of radio frequency energy in this band are published by the Federal Communications Commission (FCC) in the Code of Federal Regulations (CFR), Part 47, Section 15. These rules span 56 pages, and the essence is that your transmitter is not allowed to interfere with other peoples' communications devices, including radios and televisions for example. To conform to these rules, the transmission range of the transmitter described below is small. If you operate a transmitter outside the laboratory, it is your responsibility to read and abide by these rules. They can be found in the government documents section in the basement of Shields Library.

II. CIRCUIT

Figure 2.1 shows a block diagram of the transmitter.

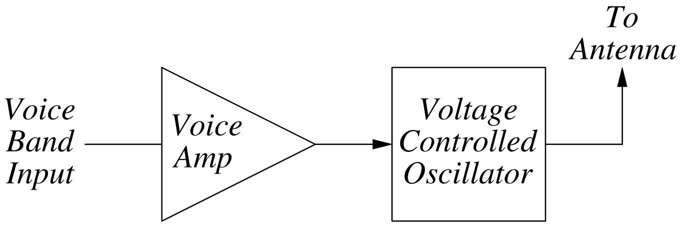

Fig. 2.1: Block Diagram of an FM Transmitter

It consists of a voice-band amplifier and voltage-controlled oscillator. Figure 2.2 shows a schematic.

The core of the voltage-controlled oscillator uses a Colpitt's structure and consists of Q_2, L_2-L_3, R_2-R_3, and C_2-C_4. Resistor R_2 sets the d.c. current in Q_2, and capacitor C_4 shorts out R_2 at the carrier frequency to allow the loop gain to be large enough for oscillation to occur. The frequency of oscillation is determined primarily by L_2 and the capacitance to ground from the base and collector leads of Q_2. Since C_4 is essentially a short circuit at the carrier frequency, C_3 should be dominant from the base to ground under ideal conditions. From the collector to ground, C_2 should be dominant under ideal conditions. In practice, however, parasitic capacitances will be important because C_2 and C_3 are small to operate in the FM band. Inductor L_1 is a radio-frequency choke. It passes the voice-band output from the amplifier to the oscillator with little loss, but attenuates the magnitude of the oscillator signal that couples back to the amplifier. Since L_1 is essentially an open-circuit at the carrier frequency, C_1 and Q_1 essentially appear to be in series at this frequency. Q_1 is operated in the cut-off region. Because the capacitance of a reverse-biased p-n junction depends on the voltage across the junction, Q_1 acts as a variable capacitance. It changes the total capacitance from the collector of Q_2 to ground, depending on the output of the voice-band amplifier. This change in capacitance changes the oscillation frequency slightly as a function of the voice-band input. That is, an FM signal is generated. Since the junction capacitance is not a linear function of the reverse-bias voltage, the frequency deviation from the carrier is also not linear here. In practice, the collector-to-substrate capacitance of Q_2 is also voltage dependent and contributes to the frequency deviation.

Inductor L_3 is a radio-frequency choke (RFC). It attenuates the feedthrough of the high-frequency carrier to the power-supply lead, reducing accidental RF radiation. (The transmitter should only broadcast from the antenna.)

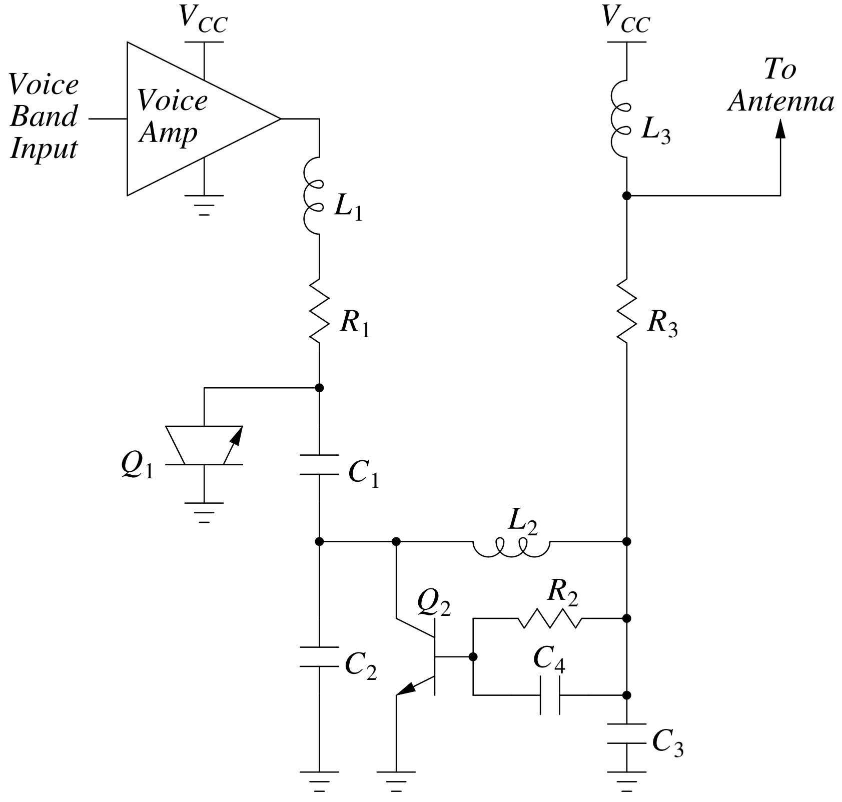

Fig. 2.2: Schematic of an FM Transmitter

The carrier wavelength in the broadcast FM band is much shorter than in the AM broadcast band. For example, a 100-MHz carrier has a wavelength of 3 meters. This reduction in the wavelength reduces the length of the required antenna in this experiment. (You may not need an antenna at all.)

III. PRE-LAB ASSIGNMENT

Use HSPICE to design the oscillator for this experiment. Use the configuration shown in Figure 2.2 and the parts shown in the parts list. The transistor models can be found on the class web page. Select R_2 to set the d.c. current in Q_2. Select C_2 and C_3 to set the frequency of oscillation to 150 ± 10 MHz using $L_2 = 0.1\ \mu H$. Although the FM band (88 MHz - 108 MHz) is the target in this experiment, the pre-lab assignment sets the simulation target to 150 MHz because the simulation does not account for parasitic capacitances and inductances that may limit the frequency of oscillation in practice. In particular, protoboards have poor performance from a parasitic standpoint.

On the day that this experiment is conducted, bring these items to lab:

1. a plot of the oscillator output (the node to which the antenna is connected) versus time calculated by HSPICE and
2. a plot showing the return-ratio magnitude versus frequency and the return-ratio phase versus frequency.

The magnitude and phase of the return ratio will be generated by a script named "rr" that will operate on the frequency-domain portion of the HSPICE output. The script will be posted on the www page for this class. If the magnitude of the return ratio is greater than one at the frequency where the phase is 180°, the oscillator will start oscillating at this frequency. In steady state, the frequency of oscillation is predicted by the time-domain portion of the HSPICE output, described in item #1 above. The 150 ± 10 MHz target should be met in the time-domain output.

IV. EXPERIMENT

For this experiment, you should use $V_{CC} = 12$ Volts and the same voice-band amplifier configuration that you designed in Experiment #1.

To let you observe the frequency modulation even when you are not talking into the speaker, you can use an arbitrary-waveform-generator output to provide a continuous voice-band input in parallel with the speaker acting as a microphone as in Experiment #1.

1. Using the component values calculated in the pre-lab assignment, build the oscillator without an antenna. Use an air-wound coil wound for L_2 as described in the parts list. Strip the enamel from the ends before winding it. About 5 turns tightly wound around a standard pencil will give about 0.1 μH to 0.2 μH. However, L_2 is too small to measure on the LCR meters in the lab. To minimize parasitic inductances, keep the leads of your components as short as possible and place your components as close together as possible on the protoboard. At first, do not connect the voice amplifier. Instead, connect the top of inductor L_1 to a 6-Volt power supply. Let us call this supply "V_{IN}". Set $V_{IN} = 6$ Volts. Measure the frequency and amplitude of the oscillator output. If necessary, change the design and/or layout of your oscillator so the output frequency is in the FM band. Operation at such a high frequency on a protoboard may not be easy. In particular, protoboards have a large parasitic capacitance (about 5 pF) from any one row of pins to the next. Also, because protoboards do not usually use a ground plane, the inductance in the ground connection may be high.
2. Measure and record the output frequency versus V_{IN} for $3 \le V_{IN} \le 9$ Volts. Is the characteristic linear? Should it be linear? What is the maximum frequency deviation?
3. Disconnect V_{IN} from L_1 and connect the voice-band amplifier to L_1. If the oscillation frequency is in the FM band, and if a standard FM receiver is available, try to transmit to it without an antenna. Keep the volume low enough that you do not disturb others in the lab, and cooperate with others in the lab to avoid transmitting signals that interfere with those transmitted by other groups. If necessary, adjust the gain of the voice-band amplifier so that input from the speaker is easily observable. Over what distance can a standard FM receiver receive transmissions from your transmitter? If necessary, repeat using a piece of insulated wire no longer than 1 foot as an antenna. If you were unable to reach 88 MHz, you may be able to receive the transmission with an FM radio that also operates in the band from 54-88 MHz. Some FM radios offer reception in this band because FM was also used to carry the sound in NTSC (National Television System Committee) television systems. Channels 2-6 in the VHF (very high frequency) band used to be broadcast between 54 MHz and 88 MHz.

4. Measure the power dissipated from the V_{CC} supply.
5. Reduce V_{CC} to the minimum value required to keep the transmitter working and record this value of V_{CC}. Measure the power dissipated from the reduced V_{CC} supply and the new oscillation frequency.
6. Spread the coil out and re-measure the carrier frequency. Strum the coil as though it is a guitar string and listen to the output on an FM radio if possible. Explain what you hear.
7. Demonstrate your transmitter to your TA.
8. If possible, keep the transmitter intact so that you can test it with the FM receiver that you will build in Experiment #4.

V. REPORT

For your report, describe what you expect to observe in each of the parts of the experiment above and explain (where applicable).

UNIVERSITY OF CALIFORNIA, DAVIS
College of Engineering
Department of Electrical and Computer Engineering

EEC 112
Experiment #3
AM Heterodyne Receiver

PARTS LIST

R_{11}	820 Ω	R_{12}	3.9 kΩ
R_{13}	1.2 kΩ	R_{14}	1 kΩ
R_{15}	1 kΩ	R_{16}	820 Ω
R_{17}	1 kΩ	R_{18}	1 kΩ
R_{19}	1 kΩ	R_{21}	5.1 kΩ
R_{22}	5.1 kΩ	R_{23}	20 kΩ
R_{24}	10 kΩ	R_{25}	10 kΩ
R_{31}	1 kΩ	R_{32}	1 kΩ
R_{33}	20 kΩ	R_{34}	10 kΩ
R_{35}	To be determined	R_{41}	10 kΩ
R_{43}	10 Ω		
R_{42}	10 kΩ Single-Turn Cermet Potentiometer PC Mount, 3 Leg, 90°, ESS # CRST103-P or equiv.		
C_{11}	0.01 μF - 0.1 μF	C_{12}	0.01 μF - 0.1 μF
C_{13}	0.01 μF - 0.1 μF	C_{14}	0.01 μF - 0.1 μF
C_{15}	0.01 μF - 0.1 μF	C_{17}	0.01 μF - 0.1 μF
C_{18}	0.01 μF - 0.1 μF	C_{21}	0.01 μF - 0.1 μF
C_{31}	0.01 μF - 0.1 μF	C_{32}	To be determined
C_{41}	0.01 μF - 0.1 μF	C_{42}	0.01 μF - 0.1 μF
C_{43}	1 μF	C_{44}	0.047 μF
C_{45}	0.01 μF - 0.1 μF	C_{46}	100 μF
L_{21}	10 mH Molded Plastic (ESS #1N10MH or equiv.)		
L_{41}	10 mH Molded Plastic (ESS #1N10MH or equiv.)		
L_{42}	1 mH Epoxy Dipped (Mouser #43LR103 or equiv.)		
Y_1	455 kHz Ceramic Filter; Bandwidth (-6 dB) = 12 kHz Input Impedance = 2.5 kΩ; Output Impedance = 2.5 kΩ (Digi-Key #TK2334-ND, Toko #HCFM2-455E, or equiv.)		
Mixer	LM1496	Power Amplifier	LM386
IF Amplifier	LM3086	Detector	LM3086

All resistors should be able to dissipate at least 1/4 Watt and all capacitors should be able to withstand at least 20 V.

I. INTRODUCTION

Heterodyne receivers mix inputs centered around two different frequencies and bandpass filter the result to select a band around the difference between the two input frequencies. One of the inputs often comes from an antenna, and the other from a local oscillator. The local-oscillator frequency is adjusted so that it differs from the carrier frequency of the desired antenna input by the center frequency of the bandpass filter, f_{IF}, which is referred to as the "intermediate frequency." Unlike simple tuned-radio-frequency receivers, heterodyne receivers can provide nearly constant selectivity. Also, heterodyne receivers are insensitive to d.c. offsets and local-oscillator leakage because of the bandpass filter. However, with simple mixers that do not keep track of the polarity of the difference between the two input frequencies, heterodyne receivers suffer from an image-rejection problem. That is, they not only sense inputs whose carrier frequency is less than the local-oscillator frequency by f_{IF}, but also inputs whose carrier is greater than the local-oscillator frequency by f_{IF}. In practice, overcoming the image-rejection problem requires the use of an external filter, which increases power dissipation and limits portability.

II. CIRCUIT

Figure 3.1 shows a block diagram of the receiver.

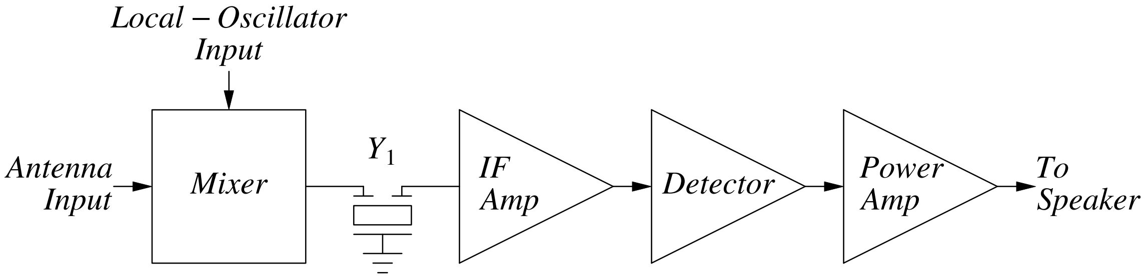

Fig. 3.1: Block Diagram of an AM Heterodyne Receiver

It consists of a mixer, a 455-kHz crystal bandpass filter (Y_1), an intermediate-frequency (IF) amplifier, a detector, and a power amplifier.

Figure 3.2 shows the mixer schematic. It consists of an LM1496 balanced modulator-demodulator and miscellaneous resistors and capacitors. The components drawn with thin lines are inside the LM1496 integrated circuit (IC). The circled numbers in Fig. 3.2 represent the external pin numbers of the LM1496 in a 14-pin DIP. The data sheet for the LM1496 can be found on the class web page as indicated in Section VII on or near page 4 of this lab manual. R_{13}, R_{16}, and R_{19} set the d.c. bias voltages at the bases of the differential pairs. R_{12} sets the d.c. bias current in the LM1496. C_{18} connects the emitters of Q_5 and Q_6 together at high frequencies. The antenna input is applied to pin #1 through C_{13}, and the local-oscillator input is applied to pin #10 through C_{11}. In this experiment, the antenna input should be small so the mixer responds almost linearly to the antenna input. On the other hand, the local-oscillator input should be large so that Q_1-Q_4 behave as switches, effectively producing an output that is ±1 times the antenna input. Since R_{11} is a small resistor, the switching in Q_1-Q_4 is done without saturating these transistors. Therefore, this multiplication can be done at high speed. If the antenna input is at frequency f_I and the local-oscillator input is at frequency f_{LO}, the mixer output contains components at $|f_I \pm f_{LO}|$. One advantage of the balanced mixer is that the output contains no components at f_{LO} or its harmonics if the mixer is perfectly balanced.

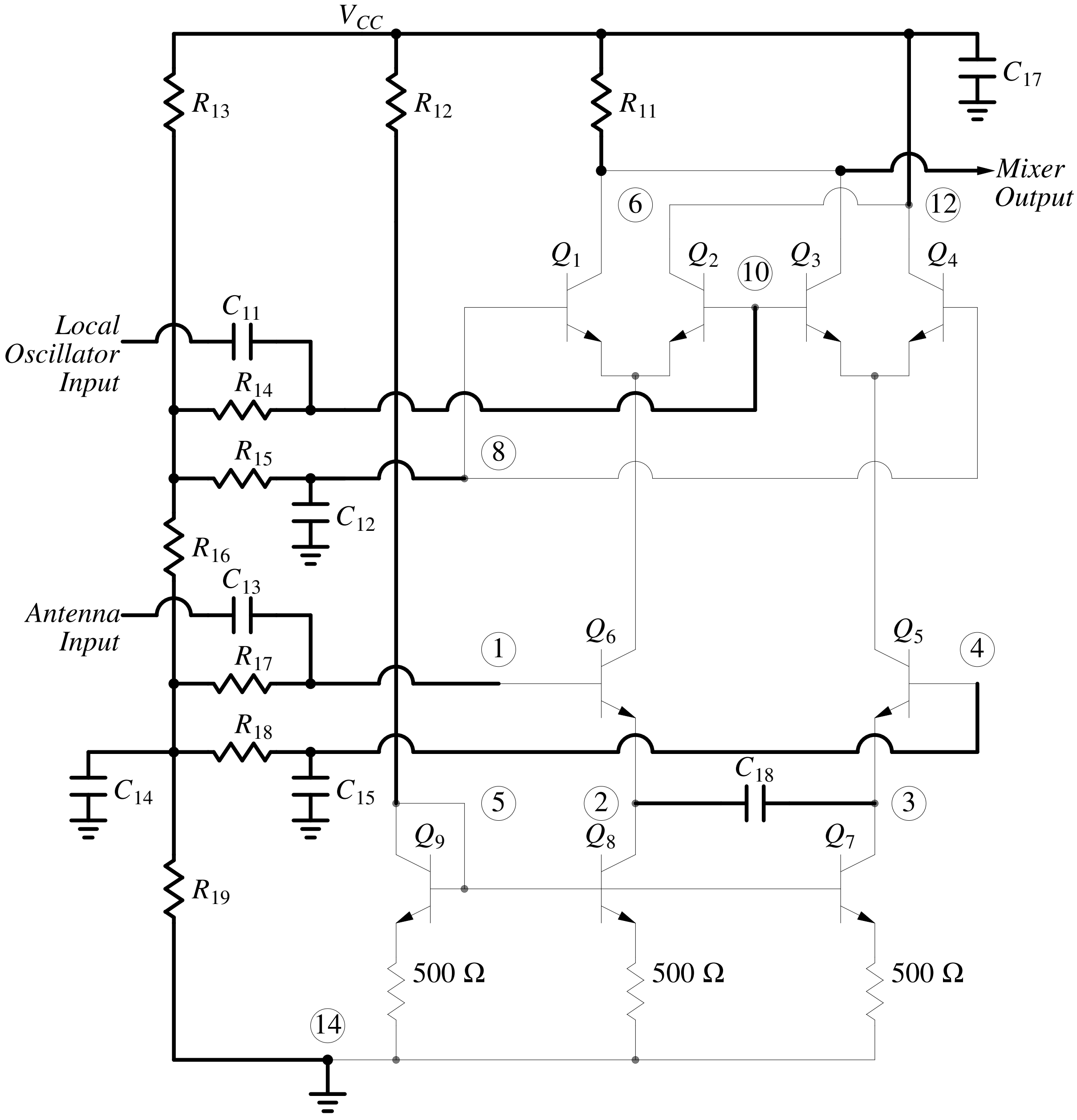

Fig. 3.2: Mixer Schematic (Components with thin lines are inside LM1496)

The mixer output is bandpass filtered by the ceramic filter (Y_1). The center frequency of the ceramic filter is about 455 kHz. Therefore, all mixer outputs except those in a small frequency band near $f_{IF} \approx 455$ kHz are heavily attenuated before sent to the intermediate-frequency (IF) amplifier. Figure 3.3 shows the schematic of the IF amplifier. It consists of an

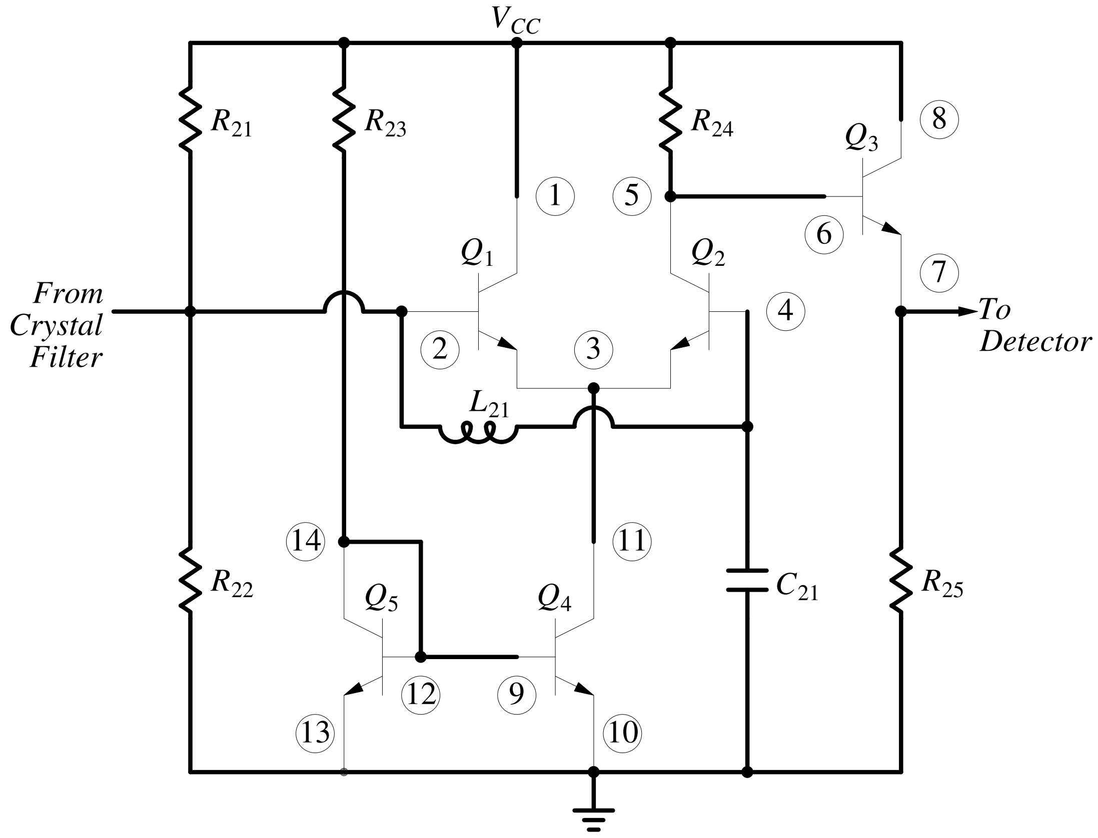

Fig. 3.3: IF Amplifier Schematic (Components with thin lines are inside LM3086)

LM3086 transistor array along with miscellaneous resistors, capacitors, and an inductor. The components drawn with thin lines are inside the LM3086 IC. The circled numbers in Fig. 3.3 represent the external pin numbers of the LM3086 in a 14-pin DIP. Note that pin #13, the substrate of the IC, is connected to ground, which is the lowest power-supply voltage here. The LM3086 is configured here as a differential pair (Q_1 - Q_2) biased by a current mirror (Q_4 - Q_5) and buffered by an emitter follower (Q_3). R_{21} and R_{22} set the d.c. bias voltage at the base of Q_1, and L_{21} and C_{21} pass this bias voltage to the base of Q_2 but greatly attenuate signals above d.c. R_{23} sets the d.c. bias current in the LM3086. R_{24} acts as a resistive load to the differential pair. Note that in many practical receivers, R_{24} - R_{25} and Q_3 are replaced by a transformer tuned to f_{IF} to improve the receiver selectivity and to reduce the effect of loading from the next stage. Here, the emitter follower (Q_3 and R_{25}) overcomes the effect of loading. A transformer is not used because the external package of commercially available IF transformers cannot plug directly into protoboards. Omission of a tuned IF transformer here reduces the selectivity of the receiver built in this experiment.

To demodulate the AM signal, a simple diode detector (which consists of a diode, a resistor, and a capacitor) can be used. A key problem with this approach, however, is that practical diodes require a bias voltage of about 0.5 Volts to turn on. To overcome this problem, most commercial AM receivers use more than one IF amplifier stage so that the IF gain is very large. On a protoboard, however, this approach is difficult to implement because increasing the IF gain increases the chance that oscillation will occur through one of the many parasitic feedback paths present on the protoboard. To overcome this problem here, a precision rectifier circuit will be used. Precision rectifiers reduce the effect of the voltage required to turn on the diode through the use of a local negative feedback loop [1, 2].

Figure 3.4 shows the schematic of the detector (or AM demodulator). It consists of an LM3086 transistor array along with miscellaneous resistors, capacitors, and an inductor, and its structure is similar to that of the IF amplifier shown in Figure 3.3. Q_1 - Q_2 and R_{34} form a differential amplifier with a resistive load, which is biased by current mirror Q_4 - Q_5. The amplifier output is connected to an AM demodulator, which consists of Q_3, R_{35}, and C_{32}. Q_3 and R_{35} form a voltage rectifier, and C_{32} reduces the rate at which the demodulated output can change when Q_3 is off. The output is connected back to the base of Q_2 to close a negative feedback loop that reduces the effect of the V_{BE} required to turn on Q_3 by the amount of the loop gain. Since the feedback factor here is unity, the loop gain is the gain of the differential amplifier. Note that R_{33} sets the current in the current mirror and R_{34} sets the current in Q_2 when Q_3 is on.

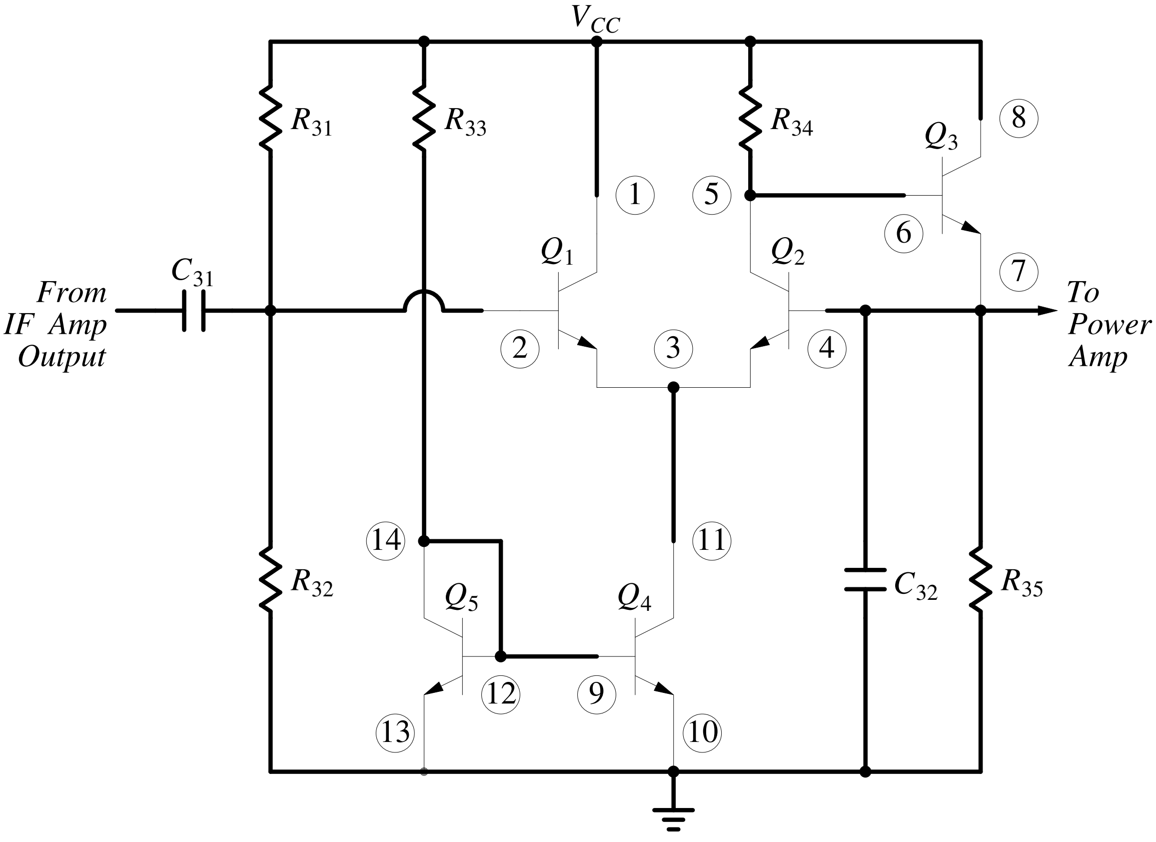

Fig. 3.4: Detector Schematic (Components with thin lines are inside LM3086)

Figure 3.5 shows the schematic of the power amplifier. It consists of an LM386 audio power amplifier, which can drive the 8-Ω speaker, along with miscellaneous resistors, capacitors, and inductors. The circled numbers in Fig. 3.5 represent the external pin numbers of the

LM386 in an 8-pin DIP. The data sheet for the LM386 can be found on the world-wide web as indicated in Section VII on or near page 4 of this lab manual. The internal configuration of the LM386 allows its inputs to be biased to ground even though ground is the lowest supply voltage. Capacitor C_{43} is used here to bypass an internal resistor and increase the closed-loop gain of the LM386 from about 20 to about 200. Resistors R_{41} - R_{42} form a variable voltage divider that will be used here as a volume control. Capacitor C_{44} and R_{43} shunt the output to suppress oscillation of the LM386 during negative swings with large loads. Inductor L_{42} and capacitors C_{45} - C_{46} band-pass filter the power-amplifier output.

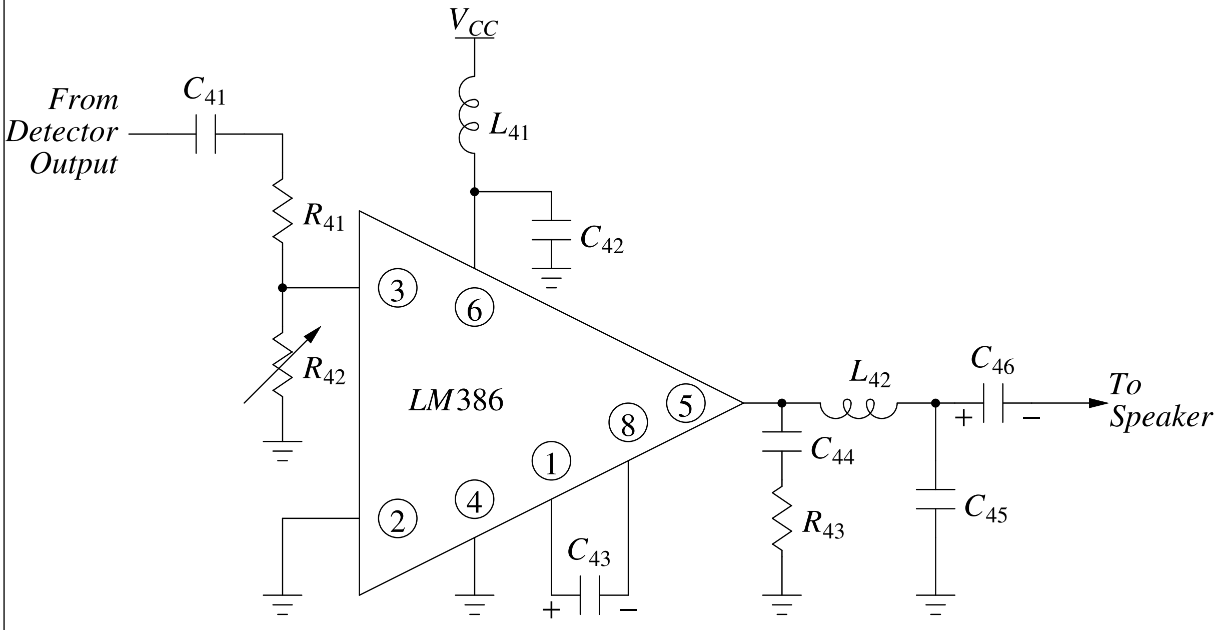

Fig. 3.5: Power-Amplifier Schematic

III. PRE-LAB ASSIGNMENT

Let V_{CC} = 12 Volts for these calculations.

1. In Figure 3.2, calculate the d.c. bias voltages from each pin of the LM1496 mixer to ground.
2. In Figure 3.4, calculate the d.c. bias voltages from each pin of the LM3086 transistor array to ground when Q_3 operates in the forward-active region. Under this condition, calculate the loop gain.
3. Balancing the issues of distortion and carrier feedthrough, select values of R_{35} and C_{32} in Figure 3.4 to demodulate the AM signal. Use these values in HSPICE to simulate the detector circuit. Because models for the transistors in the array are not available, use models for 2N3904 transistors that will be posted on the class web page. Re-simulate with other values for R_{35} and C_{32} until you understand what happens when they are too big and too small.

IV. EXPERIMENT

For this experiment, you should use V_{CC} = 12 Volts and the first channel of the arbitrary-waveform generator to provide the antenna input unless otherwise stated. Also, you should use the second channel of the arbitrary-waveform generator as the local oscillator.

1. Build the mixer shown in Figure 3.2. Take your time and do a good job the first time because the mixer is the key circuit in this and the remaining experiments. Measure the d.c. voltages to ground from all the pins of the LM1496 and compare to your pre-lab calculations. Each measured bias point should each be within 200 mV of the corresponding calculated value.
2. Build the detector shown in Figure 3.4, and leave space on your board between the mixer and detector for the IF amplifier shown in Figure 3.3. Measure the d.c. voltages to ground from all the pins of the LM3086 and compare to your pre-lab calculations.
3. Connect the mixer output to the detector input through the crystal filter, Y_1. Set the local-oscillator input to a 200 mVp-p square wave at 1.6 MHz. Set the antenna input to a 100 mVp-p sine wave at (1600-455) kHz = 1145 kHz. Observe the mixer output and the crystal-filter output as a function of the antenna input frequency.
4. Adjust the antenna input frequency to maximize the crystal-filter output. Apply sinusoidal AM with a frequency of 500 Hz and a modulation index of 50% to the antenna input. Observe the detector output. Repeat while changing the index and frequency of modulation. Is the amplitude of the output a linear function of the index of modulation?
5. Observe the detector output as a function of the peak-to-peak amplitude of the local-oscillator input.
6. Study the image problem by changing the carrier frequency of the antenna input to another value to which your receiver should be sensitive. Observe the detector output.
7. If time allows, build the power amplifier shown in Figure 3.5 and connect to the detector output. Adjust R_{42} so that the volume is low enough that you do not disturb others in the lab. Listen to the outputs generated in parts 4 and 5.
8. If your AM transmitter from Experiment #1 is available, try transmitting to your receiver.
    a. If you built a stand-alone oscillator for the AM transmitter in Experiment #1, use the first channel of the arbitrary-waveform generator to provide a continuous voice-band input in parallel with the microphone in the transmitter (as in Experiment #1) instead of as the antenna input in the receiver.
    b. If you did not build a stand-alone oscillator for the AM transmitter in Experiment #1, use the first channel of the arbitrary-waveform generator as the oscillator in the transmitter instead of as the antenna input in the receiver.
    c. Connect a short piece of insulated wire to the antenna input or directly to pin #1 of the mixer. (C_{13} is not required as long as the antenna input floats.) Try transmitting to your receiver.
    d. Build the IF amplifier shown in Figure 3.3. To test the IF amplifier by itself, couple the test input through a 0.1 μF capacitor to avoid disrupting the d.c. operating point of the IF amplifier. Compare the performance of the receiver with the IF amplifier to that without it. Note that the receiver in this lab does not have automatic gain control. As a result, you will probably have to adjust the antenna

position so that the antenna input is neither so big that it overloads the receiver nor so small that it cannot be detected by the receiver.

9. Demonstrate your receiver to your TA.
10. If possible, keep the mixer, IF amplifier, and power-amplifier circuits intact because you may use them again in Experiments #4 and #5.

V. REPORT

For your report, describe what you expect to observe in each of the parts of the experiment above and explain (where applicable).

VI. REFERENCES

[1] P. R. Gray, P. J. Hurst, S. H. Lewis and R. G. Meyer, *Analysis and Design of Analog Integrated Circuits,* p. 702-708, Wiley, New York, 2001, Fourth Edition.

[2] A. S. Sedra and K. C. Smith, *Microelectronic Circuits,* p. 1378-1386, Oxford, New York, 2010, Sixth Edition.

UNIVERSITY OF CALIFORNIA, DAVIS
College of Engineering
Department of Electrical and Computer Engineering

EEC 112
Experiment #4
FM Heterodyne Receiver

Mehmet Aslan and Stephen Lewis

PARTS LIST

R_{11}	820 Ω	R_{12}	3. 9 kΩ
R_{13}	1. 2 kΩ	R_{14}	1 kΩ
R_{15}	1 kΩ	R_{16}	820 Ω
R_{17}	1 kΩ	R_{18}	1 kΩ
R_{19}	1 kΩ	R_{21}	5. 1 kΩ
R_{22}	5. 1 kΩ	R_{23}	1 kΩ
R_{24}	1 kΩ	R_{31}	To be determined
R_{41}	10 kΩ	R_{43}	10 Ω
R_{42}	10 kΩ Single-Turn Cermet Potentiometer PC Mount, 3 Leg, 90°, ESS # CRST103-P or equiv.		
C_{11}	0. 01 μF - 0. 1 μF	C_{12}	0. 01 μF - 0. 1 μF
C_{13}	0. 01 μF - 0. 1 μF	C_{14}	0. 01 μF - 0. 1 μF
C_{15}	0. 01 μF - 0. 1 μF	C_{17}	0. 01 μF - 0. 1 μF
C_{18}	0. 01 μF - 0. 1 μF	C_{21}	0. 01 μF - 0. 1 μF
C_{31}	To be determined	C_{32}	0. 01 μF - 0. 1 μF
C_{41}	0. 01 μF - 0. 1 μF	C_{42}	0. 01 μF - 0. 1 μF
C_{43}	1 μF	C_{44}	0. 047 μF
C_{45}	0. 01 μF - 0. 1 μF	C_{46}	100 μF
L_{21}	10 mH Molded Plastic (ESS #1N10MH or equiv.)		
L_{41}	10 mH Molded Plastic (ESS #1N10MH or equiv.)		
L_{42}	1 mH Epoxy Dipped (Mouser #43LR103 or equiv.)		
Y_1	10.7 MHz Ceramic Filter; Bandwidth (-3 dB) = 230 kHz Maximum Insertion Loss = 6 dB Input Impedance = 330 Ω; Output Impedance = 330 Ω (Digi-Key #TK2306-ND, Toko #SK107M2-A0-00 or equiv.)		
Mixer	LM1496	Detector	LM1496
IF Amplifier	LM3086	Power Amplifier	LM386

All resistors should be able to dissipate at least 1/4 Watt and all capacitors should be able to withstand at least 20 V.

I. INTRODUCTION

The front end of the heterodyne receiver in this experiment is similar to the front end of AM heterodyne receiver in the last experiment with one exception. That is, the intermediate frequency, f_{IF}, here is 10.7 MHz as in standard broadcast FM receivers (instead of 455 kHz for broadcast AM). The key reason for this change is to simplify the required image-reject filter. The image-reject problem stems from a property of simple mixers: they sense not only inputs whose carrier frequency is less than the local-oscillator frequency by f_{IF}, but also inputs whose carrier frequency is greater than the local-oscillator frequency by f_{IF}. Therefore, the bandwidth that separates the desired input from the undesired image is $2f_{IF}$, and increasing f_{IF} simplifies filtering of the image. On the other hand, the value of f_{IF} is limited by the Q of practical tuned circuits in the intermediate-frequency (IF) amplifier. This is because the -3-dB bandwidth, f_{-3dB}, of a tuned circuit around f_{IF} is f_{IF}/Q. This bandwidth determines the selectivity of the receiver. (Selectivity is a measure of the number of channels that the receiver can separate from each other). With $f_{IF} = 10.7$ MHz and $Q \approx 100$, $f_{-3dB} \approx 100$ kHz, which allows adjacent channels to be separated by 200 kHz, as in broadcast FM.

II. CIRCUIT

Figure 4.1 shows a block diagram of the receiver.

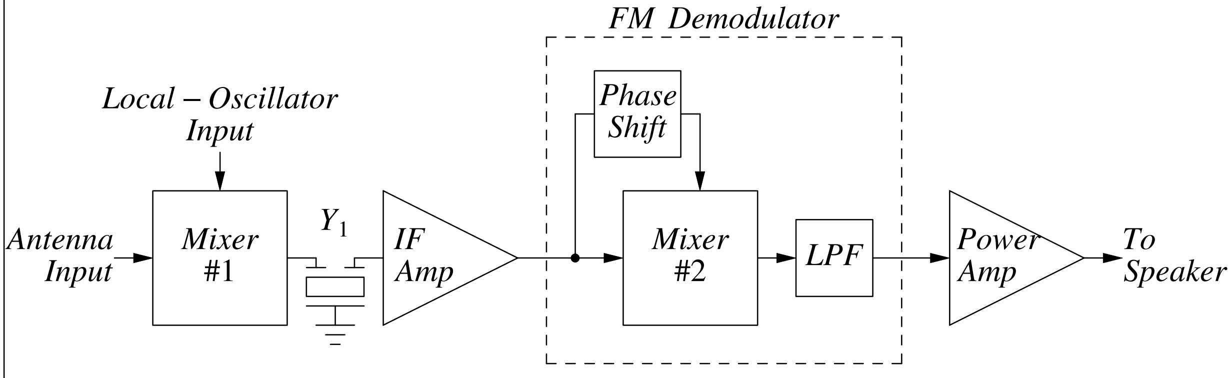

Fig. 4.1: Block Diagram of an FM Heterodyne Receiver

It consists of a mixer at the input, a 10.7-MHz crystal bandpass filter (Y_1), an intermediate-frequency (IF) amplifier, an FM demodulator, and a power amplifier. The FM demodulator uses the configuration of a quadrature detector and contains a second mixer, a phase-shift circuit, and a low-pass filter (LPF).

Figure 4.2 shows the mixer schematic. The two mixers here are the same as the one used in the AM heterodyne receiver.

The mixer output is bandpass filtered by the ceramic filter (Y_1). The center frequency of the ceramic filter is about 10.7 MHz. Therefore, all mixer outputs except those in a small frequency band near $f_{IF} \approx 10.7$ MHz are heavily attenuated before sent to the intermediate-frequency (IF) amplifier. Figure 4.3 shows the schematic of the IF amplifier. It is similar to the IF amplifier used in the AM heterodyne receiver. The main difference is that R_{23} and R_{24} here are greatly reduced compared to the values selected in the AM IF amplifier. This decrease in

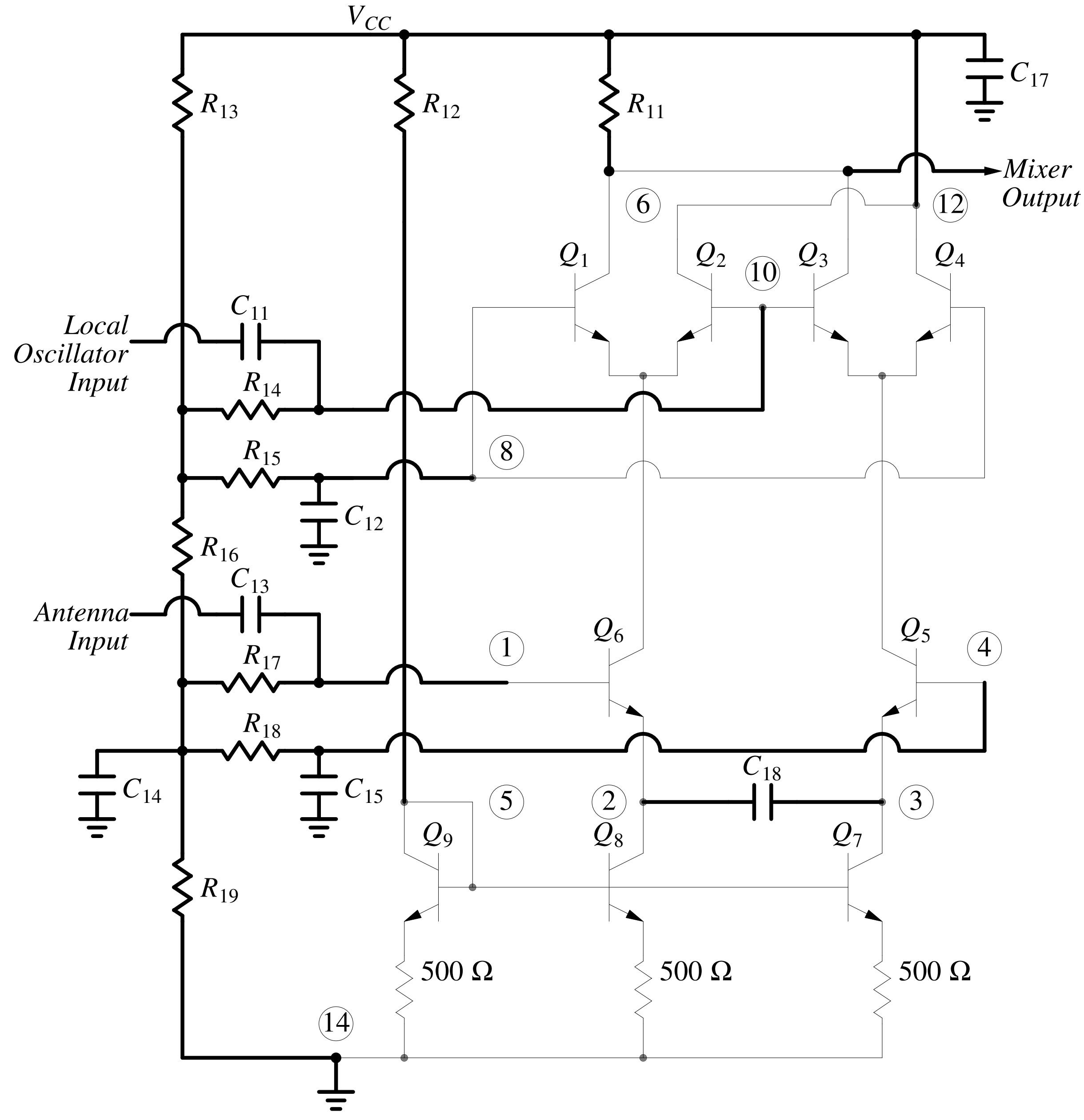

Fig. 4.2: Mixer Schematic (Components with thin lines are inside LM1496)

resistor values increases the bias current and the bandwidth of the amplifier, which is required here to cope with the increase of f_{IF} from 455 kHz to 10.7 MHz. Also, the decrease in R_{24} eliminates the need for an emitter-follower buffer at the output of the IF amplifier.

In many commercial FM receivers, the IF amplifier provides amplitude limiting; that is, it forces the peak-to-peak output amplitude to be constant for inputs above a given threshold value. Amplitude limiting is used to eliminate amplitude modulation from the input to the FM demodulator. This is important because many FM demodulators, including the one described

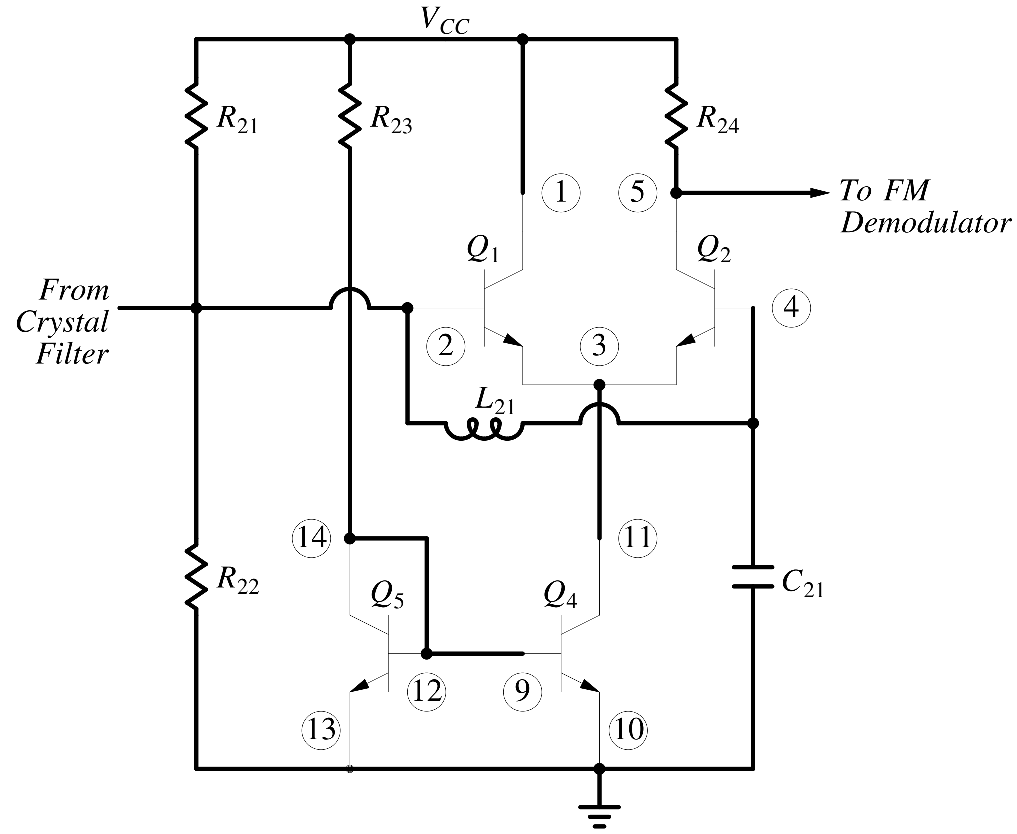

Fig. 4.3: IF Amplifier Schematic (Components with thin lines are inside LM3086)

below, are sensitive not only to FM but also to AM inputs. Classical limiters use clipping to control their output amplitude. Therefore, they convert sinusoidal inputs to square-wave outputs, generating high-frequency harmonics of f_{IF} in the process. Although classical limiting is important in FM receivers in practice, it is not used in this experiment because of difficulties imposed by protoboards. In particular, since protoboards do not usually use a ground plane, the inductance in the ground connection may be high, making the processing of harmonics of 10.7 MHz difficult. Although clipping is not expected to occur in the IF amplifier in this experiment, the gain provided by the IF amplifier here increases the likelihood that the inputs to the FM demodulator will be big enough to be seen by the demodulator as digital signals.

Figure 4.4 shows the schematic of the FM demodulator. It consists of a phase-shift network, a mixer identical to the one shown in Figure 4.2, and a low-pass filter (LPF). The demodulator uses the basic architecture of a quadrature detector, in which the input is phase shifted by an amount that depends on the input frequency. The mixer multiplies the input to the FM demodulator and its phase-shifted counterpart. Ideally, the signals applied to the mixer are big enough to turn off one transistor in each differential pair in the LM1496. Then these signals can be thought of as being digital, and the mixer acts as an exclusive-nor gate. As a result, the mixer output before filtering is low only when one of the two inputs (but not both) are low. If the phase shift between the two signals applied to the mixer is 0°, the mixer output is always at its maximum value. On the other hand, if the phase shift between the two inputs is 180°, the mixer output is always at its minimum value. To maximize the range of potential mixer outputs, the phase shift is usually set to 90° when the input frequency is f_{IF}. (Under this condition, the two inputs are said to be "in quadrature," giving rise to the name of the detector.) When the input frequency increases because of the FM on the input signal, the phase shift increases and vice versa. Because the center frequency of both inputs is f_{IF}, the main components of the mixer output before filtering are at frequencies of zero and $2f_{IF}$. As a result, the duty cycle of the $2f_{IF}$ mixer output before filtering depends on the input frequency. The LPF converts this variation in duty cycle to a variation in the amplitude of the filtered mixer output, which is passed to the power amplifier to drive the speaker. The low-pass filter is formed here by adding capacitor C_{32} from the mixer output (pin #6 of the LM1496) to ground.

To produce a phase shift of 90° at f_{IF}, the phase-shift network in a quadrature detector usually uses a tuned circuit. To simplify the construction of the circuit for this experiment, a tuned circuit is not used here. Instead, the phase-shift network here consists of capacitor C_{31} and resistor R_{31}. As a result, the range of possible phase shifts is 0° to 90°. Therefore, the phase shift is set to 45° at f_{IF}, and the circuit here is not truly a quadrature detector. The main effect of this simplification is that it reduces the range of possible mixer outputs by a factor of two.

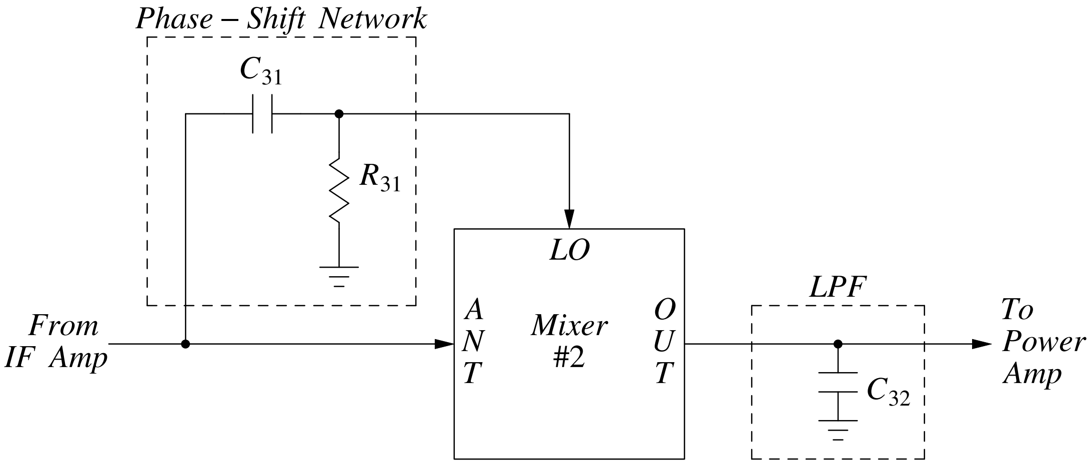

Fig. 4.4: Schematic of FM Demodulator

Figure 4.5 shows the schematic of the power amplifier. It is identical to the power amplifier used in the heterodyne receiver and repeated here for convenience.

III. PRE-LAB ASSIGNMENT

1. Assume that the frequency of the input to the phase-shift network in Figure 4.4 is f_{IN}. Write an equation for the phase shift of the phase-shift network. Is the phase-shift a linear function of f_{IN}?
2. Select the values of R_{31} and C_{31} to set the phase-shift to 45° at $f_{IN} = f_{IF} \approx 10.7$ MHz. To minimize problems with parasitics, using $R_{31} \leq 500\ \Omega$ is recommended here.

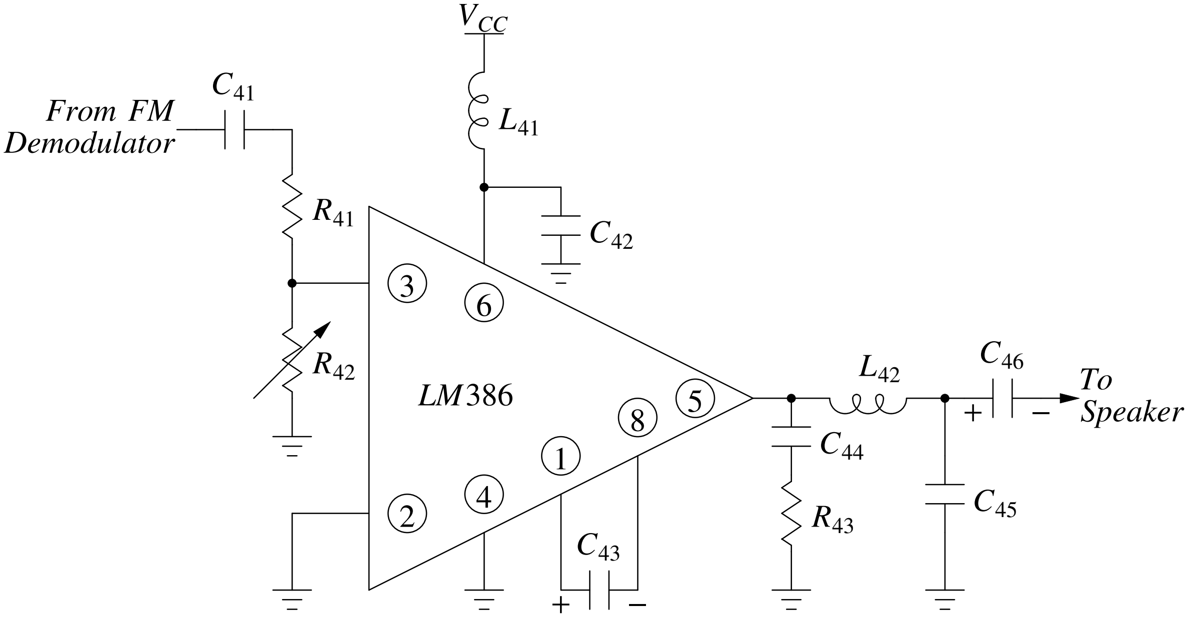

Fig. 4.5: Power-Amplifier Schematic

IV. EXPERIMENT

For this experiment, you should use V_{CC} = 12 Volts and the first channel of the arbitrary-waveform generator to provide the antenna input unless otherwise stated. Also, you should use the second channel of the arbitrary-waveform generator as the local oscillator.

1. Build and test the phase-shift network shown in Figure 4.4 using the values calculated in the pre-lab assignment. The input signal for the test should be a sine wave because the protoboards cannot handle the harmonics of a high-frequency square wave.
2. Build the back end of the FM receiver (the demodulator shown in Figure 4.4 and the power amplifier shown in Figure 4.5). Use the associated circuits from Experiment #3 wherever possible. Adjust R_{42} so that the volume is low enough that you do not disturb others in the lab.
3. Test the back end of the FM receiver as follows:
    a. Apply a 10.7-MHz sine wave as a carrier to the input of the FM demodulator. Observe the output of the power amplifier.
    b. Apply frequency modulation to the FM demodulator input. At first, use a modulating frequency of 1 kHz and a maximum frequency deviation of 10 kHz. Observe the output of the power amplifier. Repeat while changing the modulating frequency, the maximum deviation, and the carrier frequency. How does the output of the power amplifier change in each case?
    c. Disable the frequency modulation and apply amplitude modulation to the FM demodulator input. Observe the output of the power amplifier.

4. Build the IF amplifier shown in Figure 4.3. Use the associated circuits from Experiment #3 wherever possible. Measure the magnitude of the gain of the IF amplifier at 10.7 MHz.

   Keep in mind that R_{21} and R_{22} bias the dc input voltage to be greater than zero. If you connect this input directly to the output of an arbitrary-waveform generator, the dc output voltage of that generator will probably be unequal to the dc input set by R_{21} and R_{22}. In this case, the arbitrary-waveform generator would change the dc input voltage and change the gain of the IF amplifier that you are trying to measure. To overcome this problem, the connection from the arbitrary-waveform generator to the input of the IF amplifier should be made through an AC coupling capacitor. Choose the capacitance ≥ 0.01 μF so that the capacitor's impedance is a negligible factor in the measured gain. Also, choose a capacitance of ≤ 0.1 μF so that the capacitor can be both non-polarized for simplicity and inexpensive. (If you use a polarized capacitor, and if the dc output voltage of your arbitrary-waveform generator is zero, the positive terminal of the capacitor should be connected to the IF amplifier input, and the negative terminal of the capacitor should be connected to the arbitrary-waveform-generator output.)

   Is the gain frequency dependent? Connect the IF amplifier output to the input of the FM demodulator, and repeat enough of the procedure in part #3 to make sure that the circuit is working properly.
5. Build the mixer shown in Figure 4.2. It is identical to the mixer used in the FM demodulator. (Remember that the LPF, C_{32}, is not used here.) Measure the d.c. voltages to ground from all the pins of the LM1496 to help confirm that the mixer is connected correctly.
6. Remove the AC coupling capacitor that you used in step 4 to measure the gain of the IF amplifier by itself. Connect the mixer output to the IF amplifier input through the crystal filter, Y_1, as shown in Figure 4.1. Set the antenna input to a 100 mVp-p sine wave at about 14 MHz. (Note that the maximum frequency out of the arbitrary-waveform generator is 20 MHz.) Set the local-oscillator input to a 200 mVp-p square wave at about (14-10.7) MHz = 3.3 MHz. Adjust the carrier frequency on the antenna input to maximize the crystal-filter output. Loading on the crystal filter may change its center frequency slightly.
7. Apply frequency modulation to the antenna input in Figure 4.1. At first, use a modulating frequency of 1 kHz and a maximum frequency deviation of 10 kHz. Observe the output of the power amplifier. Repeat while changing the modulating frequency, the maximum deviation, and the carrier frequency. How does the output of the power amplifier change in each case?
8. Disable the frequency modulation and apply amplitude modulation to the antenna input. Observe the output of the power amplifier.
9. If time allows, try the following experiments:
   a. Observe the output of the power amplifier as a function of the peak-to-peak amplitude of the local-oscillator input.
   b. Study the image problem by changing the carrier frequency of the antenna input to another value to which your receiver should be sensitive. Observe the output of the

power amplifier.

c. If your FM transmitter from Experiment #2 is still available, disconnect the first channel of the arbitrary-waveform generator as the antenna input. Connect a short piece of insulated wire to the antenna input or directly to pin #1 of the mixer. (C_{13} is not required as long as the antenna input floats.) Increase the local-oscillator frequency in the receiver and decrease the frequency of oscillation in the transmitter so that the difference is 10.7 MHz. Try transmitting to your receiver.

10. Demonstrate your receiver to your TA.
11. If possible, keep at least one mixer and the power amplifier intact because you will use them again in Experiment #5.

V. REPORT

For your report, describe what you expect to observe in each of the parts of the experiment above and explain (where applicable).

UNIVERSITY OF CALIFORNIA, DAVIS
College of Engineering
Department of Electrical and Computer Engineering

EEC 112
Experiment #5
AM Homodyne Receiver

Mehmet Aslan and Stephen Lewis

PARTS LIST

R_1	2. 2 kΩ	R_2	1 kΩ
R_3	1 kΩ	R_4	2. 2 kΩ
R_5	100 kΩ	R_6	To be determined
R_7	100 Ω	R_8	To be determined
R_{11}	820 Ω	R_{12}	3. 9 kΩ
R_{13}	1. 2 kΩ	R_{14}	1 kΩ
R_{15}	1 kΩ	R_{16}	820 Ω
R_{17}	1 kΩ	R_{18}	1 kΩ
R_{19}	1 kΩ	R_{31}	160 Ω
R_{41}	10 kΩ	R_{43}	10 Ω
R_{42}	10 kΩ Single-Turn Cermet Potentiometer PC Mount, 3 Leg, 90°, ESS # CRST103-P or equiv.		
C_2	0. 01 µF - 0. 1 µF	C_7	1 nF
C_8	1 nF	C_9	To be determined
C_{11}	0. 01 µF - 0. 1 µF	C_{12}	0. 01 µF - 0. 1 µF
C_{13}	0. 01 µF - 0. 1 µF	C_{14}	0. 01 µF - 0. 1 µF
C_{15}	0. 01 µF - 0. 1 µF	C_{16}	0. 01 µF - 0. 1 µF
C_{17}	0. 01 µF - 0. 1 µF	C_{18}	0. 01 µF - 0. 1 µF
C_{31}	1000 pF	C_{41}	0. 01 µF - 0. 1 µF
C_{42}	0. 01 µF - 0. 1 µF	C_{43}	1 µF
C_{44}	0. 047 µF	C_{45}	0. 01 µF - 0. 1 µF
C_{46}	100 µF		
L_{41}	10 mH Molded Plastic (ESS #1N10MH or equiv.)		
L_{42}	1 mH Epoxy Dipped (Mouser #43LR103 or equiv.)		
PLL	LM565		
Mixer	LM1496		
Power Amplifier	LM386		
BNC T-connector			

All resistors should be able to dissipate at least 1/4 Watt and all capacitors should be able to withstand at least 20 V.

I. INTRODUCTION

Homodyne receivers mix two inputs centered around the same frequency and low-pass filter the result to shift a radio-frequency (RF) signal from a band around its carrier frequency to a band around zero frequency. Because the RF signal is converted directly to baseband instead of first to an intermediate frequency, these receivers are also called "direct-conversion" receivers. Homodyne structures eliminate the image-reject problem and also the need for external IF filters. However, homodyne structures are sensitive to d.c. offset, drift, and 1/f noise, which are important nonidealities especially in CMOS technologies. Other issues such as local-oscillator leakage are also limitations in the use of homodyne structures.

II. CIRCUIT

Figure 5.1 shows a block diagram of the receiver.

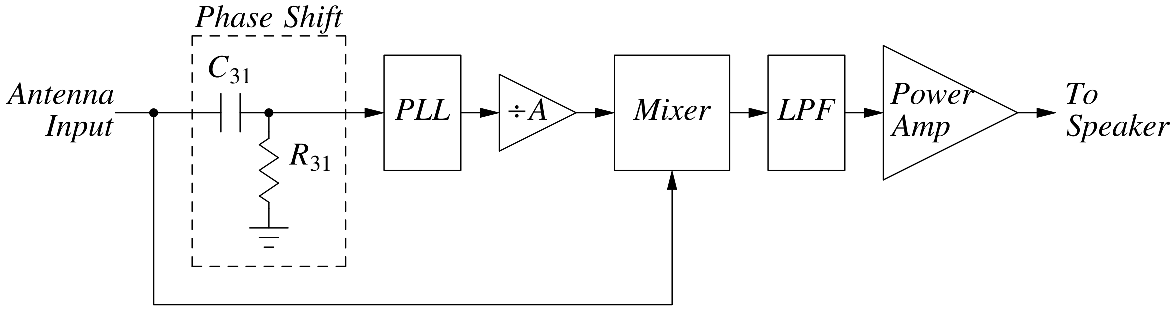

Fig. 5.1: Block Diagram of an AM Homodyne Receiver

It consists of a phase-shift network, phase-locked loop (PLL), attenuator, mixer, and a power amplifier. The PLL locks onto the carrier of the selected input and introduces a phase shift of 90° when the input frequency is equal to the free-running frequency of the PLL. The attenuator reduces the amplitude of the mixer input stemming from the PLL output to avoid overdriving the mixer. The mixer multiplies the antenna input by the attenuated PLL output, shifting the selected input to baseband where it can be recovered by a low-pass filter (LPF) and amplifier. If the two mixer inputs are separated by 90°, they are orthogonal and the output of the LPF will be zero. To overcome this problem, the phase-shift network here offsets the 90° phase shift introduced by the PLL.

Figure 5.2 shows the the PLL and attenuator schematics. The components drawn with thin lines are inside the LM565 integrated circuit (IC). The circled numbers in Fig. 5.2 represent the external pin numbers of the LM565 in a 14-pin DIP. (Pins #11, #12, #13, and #14 are unconnected.) The data sheet for the LM565 can be found on the class web page as indicated in Section VII on or near page 4 of this lab manual. The complete schematic of the LM565 is given on its data sheet. It consists of a phase detector, an amplifier, and a voltage-controlled oscillator (VCO). The phase detector (Q_1-Q_9) uses a structure similar to the LM1496 mixer with diode clamps. The amplifier (Q_{10}-Q_{11}) is a standard differential pair with emitter degeneration and a resistive load. The VCO (Q_{12}-Q_{36} and Q_{40}-Q_{41}) contains a voltage-to-current converter and a Schmitt trigger. Transistors Q_{37}-Q_{39} are used for d.c. biasing.

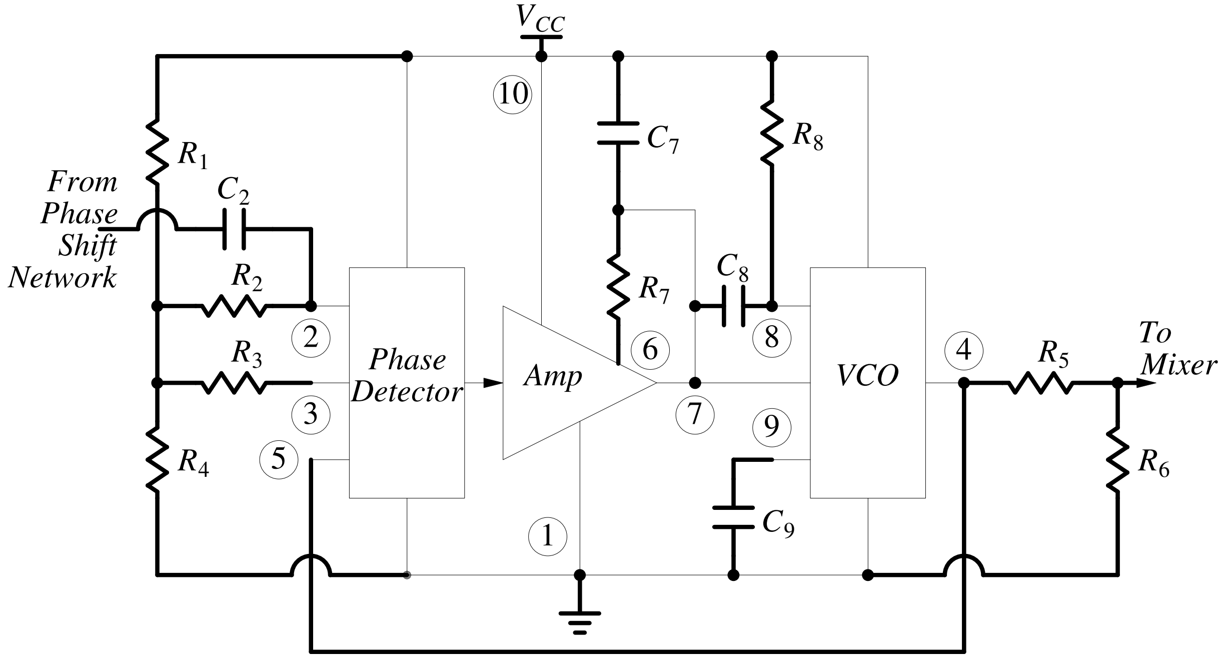

Fig. 5.2: Phase-Locked Loop and Attenuator Schematics

Resistors R_1-R_4 in Figure 5.2 set up the d.c. bias on the phase-detector inputs at pins #2 and #3. Resistors R_5-R_6 form the attenuator. Resistor R_7 reduces the load resistance at the output of the amplifier inside the LM565. Therefore, R_7 also reduces the PLL loop gain and hold and capture ranges. (In this application, the hold and capture ranges should be narrow so that the number of channels the receiver can select in the AM broadcast band is large.) The PLL loop filter is formed by the combination of this load resistance and capacitor C_7.

Resistor R_8 in Figure 5.2 and Q_{13} inside the LM565 form a voltage-controlled current source that is controlled by the voltage from pin #7 to ground (VCO input). This voltage-controlled current, $I_{C_{13}}$ sets the current that charges and discharges capacitor C_9. When $I_{C_{13}}$ flows into C_9, the voltage from pin #9 to ground rises with a slope of $I_{C_{13}}/C_9$. When this voltage reaches an upper threshold set by a Schmitt trigger inside the LM565 (Q_{25}-Q_{36}), the current in C_9 reverses and the slope of the voltage from pin #9 to ground becomes $-I_{C_{13}}/C_9$. When this voltage reaches a lower threshold set by the Schmitt trigger, the current in C_9 reverses again, and the cycle repeats. Therefore, the voltage from pin #9 to ground is a triangle wave whose frequency is controlled by the voltage from pin #7 to ground, R_8, and C_9. When the PLL is not locked, this frequency is the free-running frequency of the voltage-controlled oscillator. The free-running frequency, f_F, measured in Hz is given by:

$$f_F \approx \frac{1}{(3.7)R_8C_9} \tag{5.1}$$

The error in Equation (5.1) is small for $f_F \leq 100$ kHz. **For frequencies in the AM broadcast band, the error in Equation (5.1) can be as large as 50%** because the LM565 was designed to operate at frequencies below the AM band.

Figure 5.3 shows the schematic of the mixer and low-pass filter. The mixer is the same as that used in both the AM and FM heterodyne receivers. The low-pass filter is formed here by adding capacitor C_{16} from pin #6 of the LM1496 to ground. Low-pass filtering is required here because the mixer output in Figure 5.3 is centered around zero frequency. In contrast, C_{16} was not used in the AM heterodyne receiver because the mixer output there was centered around a non-zero IF of about 455 kHz. Therefore, band-pass filtering was required in the heterodyne receiver instead of low-pass filtering here.

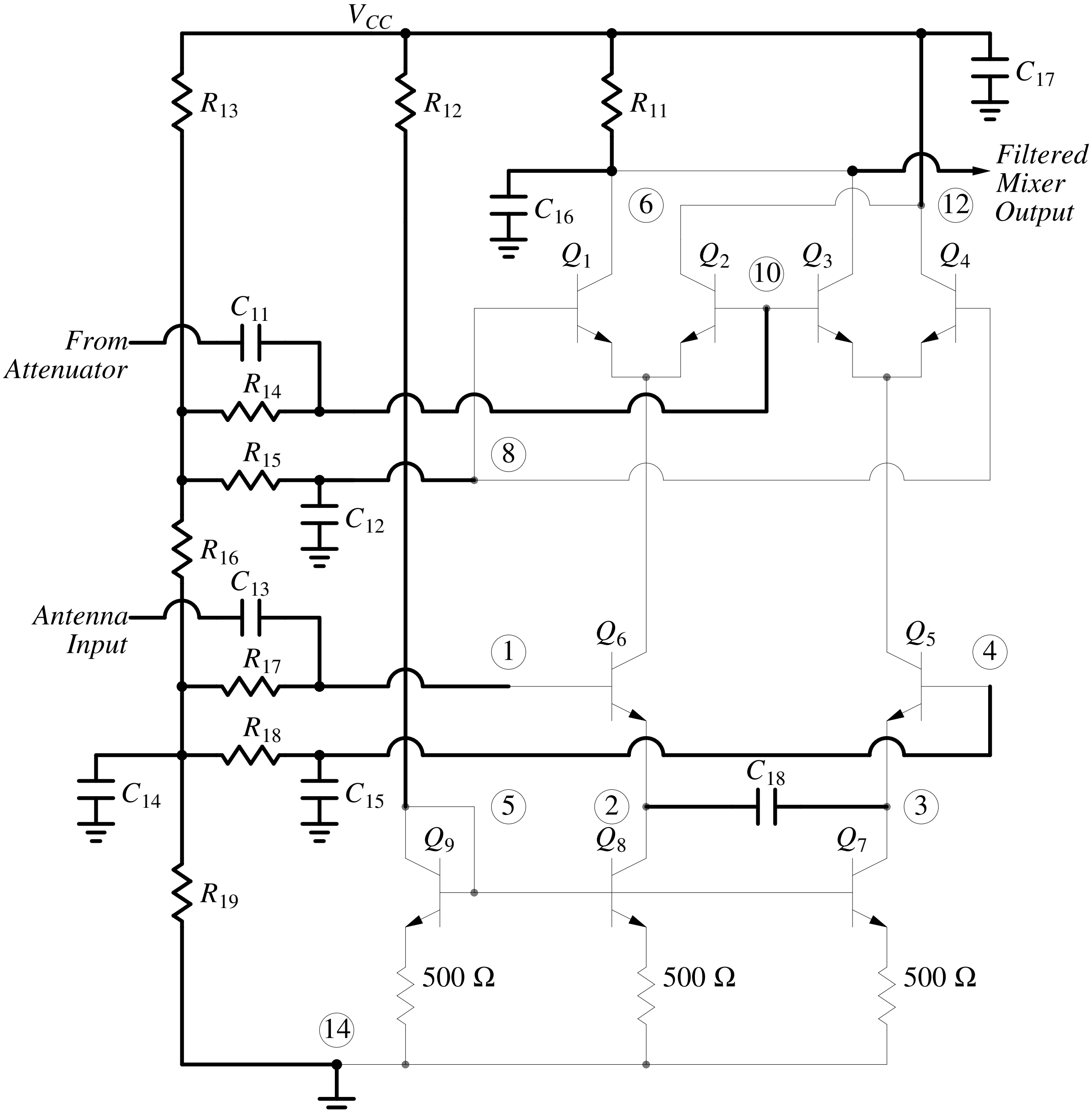

Fig. 5.3: Mixer and LPF Schematic (Components with thin lines are inside LM1496)

Figure 5.4 shows the schematic of the power amplifier. It is identical to the power amplifier used in the heterodyne receiver and repeated here for convenience.

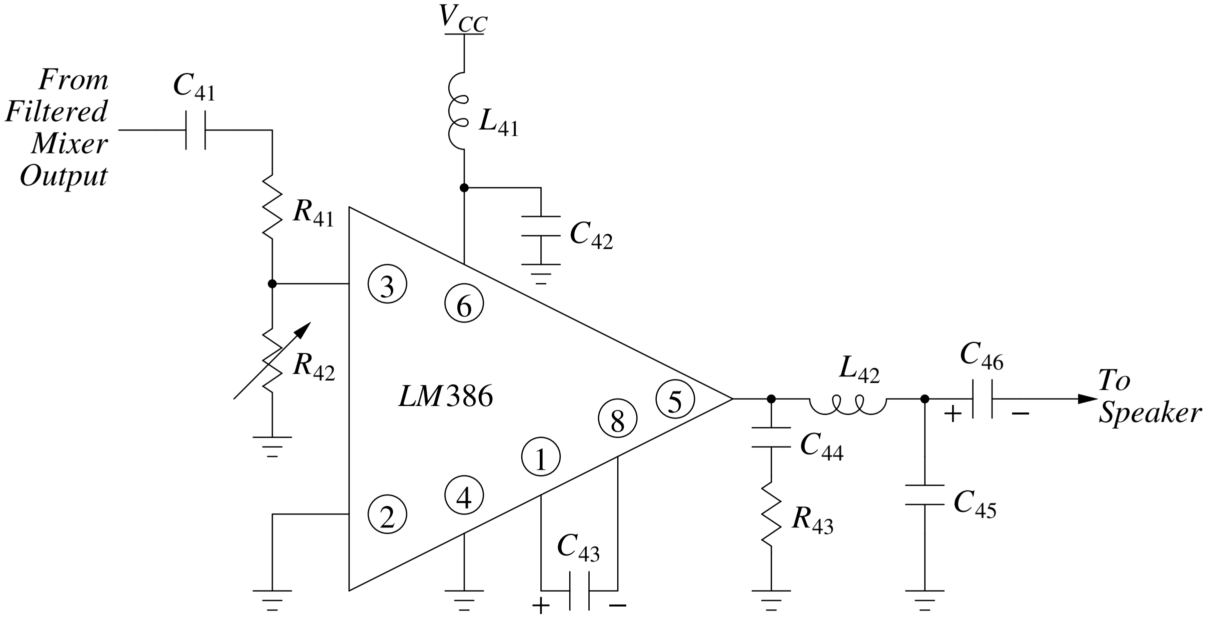

Fig. 5.4: Power-Amplifier Schematic

III. PRE-LAB ASSIGNMENT

1. Choose a carrier frequency in the AM broadcast band. If you built an oscillator for your AM transmitter in Experiment #1, choose its carrier frequency here to simplify testing your transmitter and receiver together. Call the selected carrier frequency f_C.
2. Using Equation (5.1), select the values of R_8 and C_9 in Figure 5.2 to set the free-running frequency to f_C. Since R_8 forms the degeneration resistor in a voltage-controlled current source, R_8 controls the voltage-to-current-conversion constant to the extent that it is large. Using $R_8 \geq 100\ \Omega$ is recommended here. Also, since C_9 appears in parallel with the parasitic capacitances attached to pin #9, large values of C_9 reduce the importance of the parasitics in determining the free-running frequency. Using $C_9 \geq 100$ pF is recommended here.
3. Using the value of R_5 given in the parts list, choose the value of R_6 to avoid overdriving the mixer. The PLL output is a 6-Vp-p square wave. The mixer input from the attenuator should be just large enough to turn off one transistor in each pair Q_1-Q_2 and Q_3-Q_4 in Figure 5.3.

IV. EXPERIMENT

For this experiment, you should use $V_{CC} = 12$ Volts and an output of the arbitrary-waveform generator to provide the antenna input unless otherwise stated.

1. Using the values for R_6, R_8, and C_9 calculated in the pre-lab assignment, build the PLL and attenuator shown in Figure 5.2 on the same protoboard that holds the mixer and

power amplifier from Experiment #3. Let the PLL input float (pin #2 in Figure 5.2), and measure the PLL free-running frequency, f_F, at both the LM565 output, pin 4, and at the attenuator output, the junction of R_5 and R_6. Is there a difference? If yes, why is there a difference and which measurement gives the lowest error? (Hint: the capacitance at the input of the oscilloscope probe is significant and may cause the PLL output to be slew-rate limited.) Verify your answer experimentally and summarize in your lab notebook.

2. Measure the hold range of the PLL.
   a. Connect the PLL input to an output of the arbitrary-waveform generator. Select a sine-wave output with amplitude 1 Vp-p and frequency of about f_F. The output frequency of the PLL should lock to the input frequency. Follow these steps to determine whether the PLL has locked to the input frequency:
      i. Simultaneously display both the PLL input and attenuator output on an oscilloscope. (The attenuator output is at the junction of R_5 and R_6.) A simple way to do this is to use a BNC T-connector on the arbitrary-waveform-generator output. While one side of the T-connector is connected to the PLL input, the other side of the T-connector can be connected to an oscilloscope input. A standard oscilloscope probe can be used to observe the attenuator output.
      ii. Set the oscilloscope to trigger on either the PLL input or the attenuator output but not both.
      iii. The PLL is locked onto the input when both traces are synchronized.
   b. Decrease the input frequency in steps of 1 kHz until the output frequency is no longer equal to the input frequency. Record the minimum input frequency to which the PLL remains locked.
   c. Again set the input frequency to f_F. Increase the input frequency in steps of 1 kHz until the output frequency is no longer equal to the input frequency. Record the maximum input frequency to which the PLL remains locked.
3. Measure the capture range of the PLL.
   a. Connect the PLL input to an output of the the arbitrary-waveform generator. Select a sine-wave output with amplitude 1 Vp-p and frequency small enough that the PLL output is unlocked (about 100 kHz should be fine). The output frequency of the PLL should be f_F.
   b. Increase the input frequency until the output frequency locks to the input. Record the smallest input frequency for which lock occurs. Follow the directions step 2(a) above to determine when lock occurs.
   c. Set the input frequency large enough that the PLL output is unlocked (about 10 MHz should be fine). Decrease the input frequency until the output frequency locks to the input. Record the largest input frequency for which lock occurs.
4. Connect both mixer inputs in Figure 5.3 to an output of the arbitrary-waveform generator. Set the generator output to a 100 mVp-p sine wave at the carrier frequency, f_C, that you selected in the pre-lab assignment. Add capacitor C_{16} to low-pass filter the mixer output, and connect the filtered mixer output directly to the power amplifier. Observe the output of the power amplifier as you change the amplitude of the mixer input. Capacitor C_{41} in

Fig. 5.4 should be temporarily shorted out for this measurement so that it does not block d.c. inputs to the power amplifier. Find the range of mixer inputs for which the gain is constant.

5. Disconnect the arbitrary-waveform generator from C_{11} in the mixer, and connect the attenuator output to C_{11} instead. Leave the arbitrary-waveform generator connected to C_{13}. Connect the phase-shift network (R_{31} and C_{31} in Fig. 5.1) to the PLL input (C_2 in Fig. 5.2). Apply sinusoidal AM with a frequency of 500 Hz and a modulation index of 50% to the antenna input. Change the carrier frequency of the generator, f_C, until the PLL locks to it. Observe the output of the power amplifier. Repeat while changing the index and frequency of modulation. Is the amplitude of the output a linear function of the index of modulation?
6. Replace R_8 in the PLL with a potentiometer ($\leq 10\ \text{k}\Omega$). Set the carrier frequency of the arbitrary-waveform generator to a frequency in the AM broadcast band. Adjust R_8 until the PLL locks to the carrier frequency that you selected. Repeat the measurements of part #5.
7. If your AM transmitter from Experiment #1 is still available, disconnect the arbitrary-waveform generator from the antenna input, and connect a short piece of insulated wire to the antenna input or directly to pin #1 of the mixer. (C_{13} is not required as long as the antenna input floats.) Try transmitting to your receiver. Note that the receiver in this lab does not have automatic gain control. As a result, you will probably have to adjust the antenna position so that the antenna input is neither so big that it overloads the receiver nor so small that it cannot be detected by the receiver.
8. Demonstrate your receiver to your TA.

V. REPORT

For your report, describe what you expect to observe in each of the parts of the experiment above and explain (where applicable).