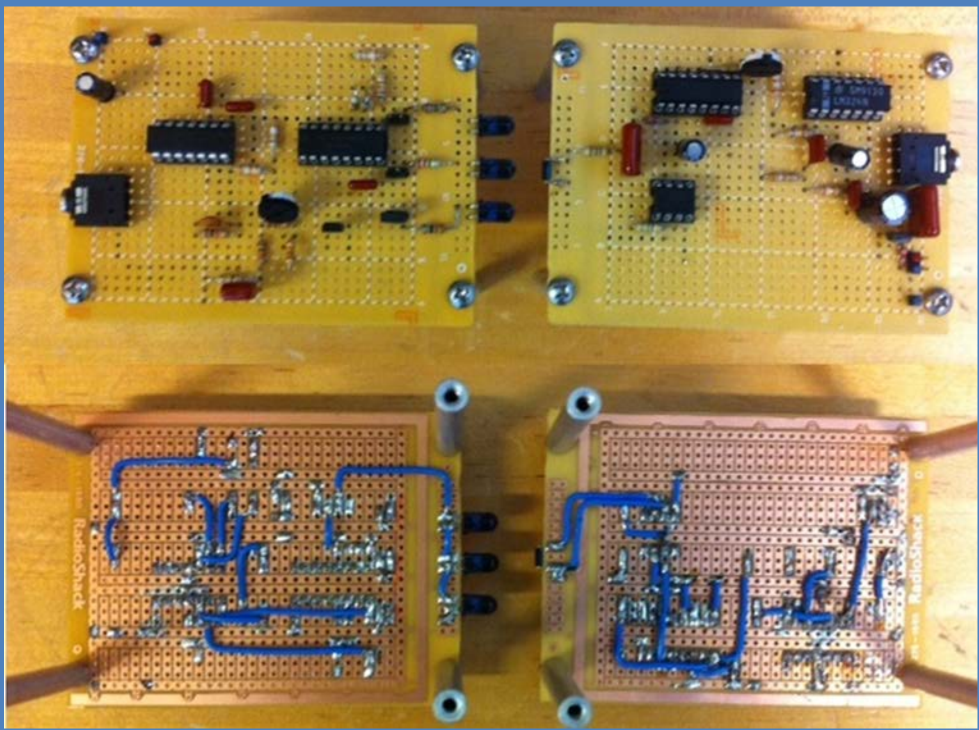
EECS 501 Lab 3 Report

Infrared FM Audio Communication System

Abstract

The goal of this laboratory was to design, construct, and test an infrared FM audio communication system. The transmitter interfaces with the PC sound card to input audio data which is frequency modulated using a voltage controlled oscillator (VCO) built to provide a quiescent sub-carrier frequency of 105 kHz. Voice-band signaling of 3 kHz is the valid audio frequency range. The transmitter uses a dynamic number of infrared LEDs (TSAL6100) to achieve multiple communication ranges. The receiver uses a phase lock loop (CD4046) to demodulate the FM signal which is received with a photodiode (BPF104). The demodulated signal is then filtered and amplified in order to drive a speaker. The detail behind the theory, construction, and analysis of this infrared FM audio communication system is outlined in the following report.



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Introduction

The infrared wireless FM audio communication system is designed to receive audio input from a PC sound card and transmit the audio signal over free-space using a VCO and a phase lock loop (PLL) to modulate and demodulate the signal. Prior to modulation the audio signal is conditioned to be frequency modulated, and is filtered to pass voice frequencies. The audio signal is modulated into a square wave with a carrier frequency and is optically transmitted by infrared LEDs and received by a photodiode and pre-amplified. The PLL demodulates the FM square wave and is fed into a audio conditioner, similar to the transmitter, that filters the output of the PLL. The signal is conditioned and AC coupled to obtain the original audio signal input. Figure 1 and Figure 2 shows a basic block diagram of the transmitter and receiver, respectively.[1]

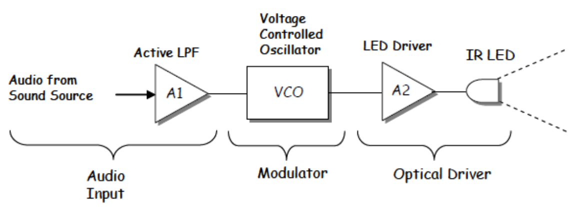

Figure 1: Block diagram of transmitter

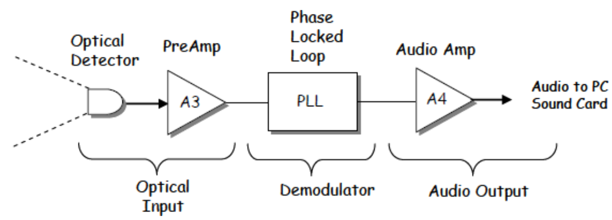

Figure 2: Block diagram of receiver

The design requirements of the FM audio communication system are outlined below.

1. Condition a voice-band audio signal of approximately 3 kHz frequency.
2. FM modulate an audio signal with a carrier frequency of 105 kHz.
3. Transmit the FM audio signal using infrared LEDs and a switching transistor, and receive the audio signal with a photodiode.
4. Obtain a phase locked loop at 105 kHz center frequency to demodulate the signal received by the photodiode.
5. Condition the received voice band audio signal to mimic the input from the PC sound card for use with external speakers.

Methodology

This design of an infrared FM audio communication system consists of a transmitter and receiver detailed in Figure 1 and Figure 2, respectively. The transmitter has input filtering, a voltage controlled oscillator, and switching infrared LED transmission stages; the receiver has a photodiode, phase lock loop, and output filtering stages. Each part detailed in Figure 3 and Figure 4 and are labeled as R1, for example, on the schematic; however, is referenced as R_1 in this document. A larger, more readable,

[1] Millennium Engineering. “Experiment 3 Instructions” <https://www.cresis.ku.edu/~callen/501/exp3.pdf>

version of both schematics are located on the EECS people servers for the [transmitter]() and the [receiver](). Note that the part labels are duplicated for each schematic for simplicity, i.e. there is an R1 for both the transmitter and receiver. Throughout this document please refer to surrounding context that denotes which component R_1, for example, is referring to.

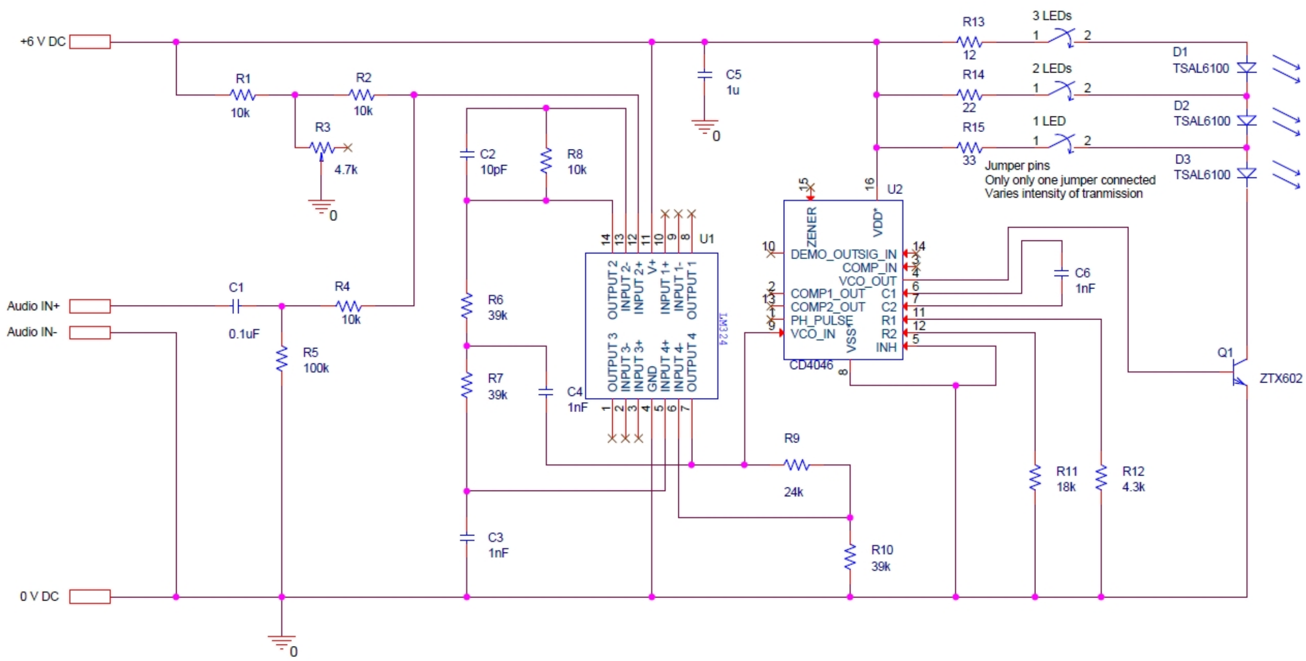

Figure 3: Transmitter schematic

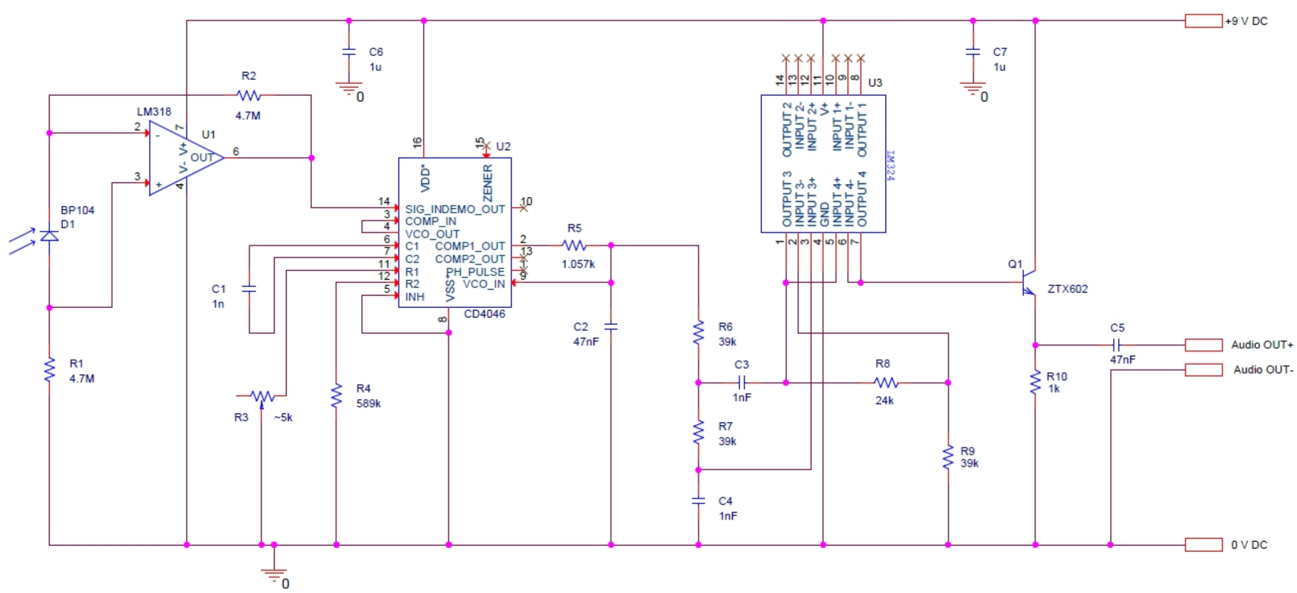

Figure 4: Receiver schematic

Input Characterization

When interfacing with a complex device such as a soundcard, it is necessary to find an equivalent model which simplifies and describes its behavior. A Thevenin equivalent model was constructed by finding the open circuit voltage, V_{oc}, and the Thevenin resistance, R_{th}, looking into the sound card. The audio jack had three pins, two channels and a ground; the two channels were connected together to avoid any coupling because only one channel was being used by the circuit and to transmit both channels of audio. V_{oc} was determined to be a function of frequency after playing 18 kHz, 8 kHz, and 2 kHz tones. Upon comparing V_{oc} from each tone, it was noticed that as the frequency decreased, the maximum V_{oc} increased. The maximum V_{oc} value was found to be 1,050 mV_{pp}. The measurement of R_{th} was more involved because short circuiting the sound card could damage it. A decade resistance box was used at different loads, and the voltage and current were measured for each. R_{th} was then approximated as the magnitude of the slope of the besting fitting linear curve that matches the dataset. These measurements were taken at 2 kHz, and R_{th} was determined to be 544 Ω; Figure 5 shows this result.

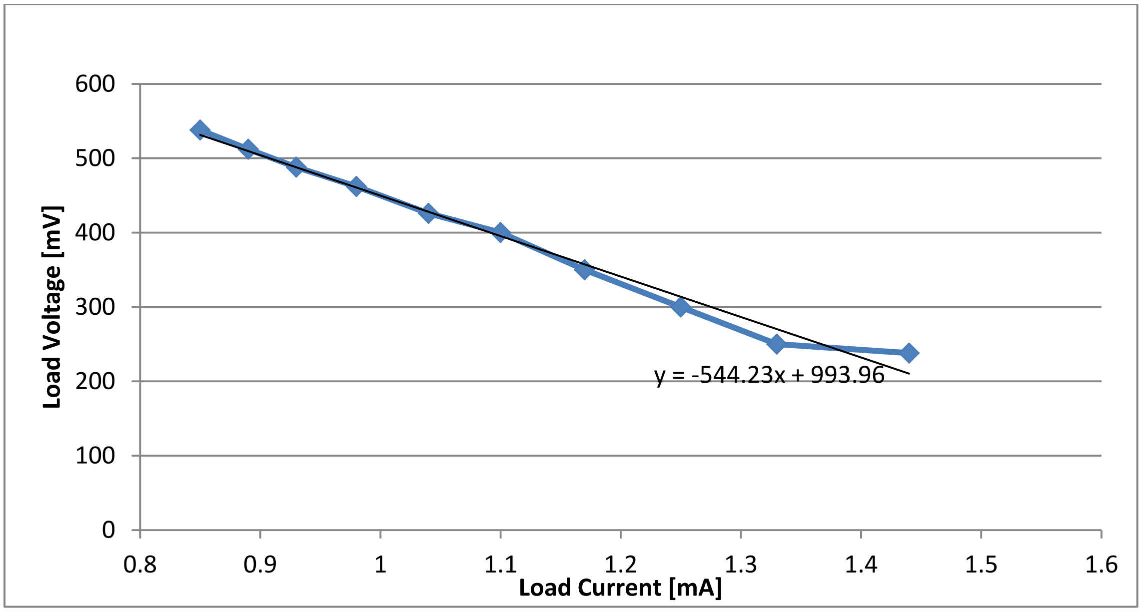

Figure 5: Categorizing sound card R_{th} value

By categorizing the sound card with its Thevenin equivalent, two issues arose that had to be handled for the sound card and the transmitters 1_{st} stage to interface properly. The first issue was that the output signal from the sound card was centered around 0 V. This is a problem because some of the circuitry cannot handle any voltage lower than 0 V due to the supply voltages. Therefore, a DC offset must be added by the 1_{st} stage on the transmitter, or half of the audio signal would be clipped off. The second issue was the possibility of loading the sound card. Since R_{th} was 544 Ω, the load resistance looking into the transmitter circuit must be much greater R_{th}. A voltage follower which has very high input impedance was used to solve this issue as well as isolate the sound card from the rest of the circuit.

Construction

Each section was implemented on the breadboard and tested individually. Both the transmitter and receiver sections were implemented on breadboards and tested to verify the whole design. Then a new set of components were ordered to implement the transmitter and receiver on proto boards. Considering the new components having slightly different values from the implemented design on the breadboards, one potentiometer was placed on the transmitter and receiver to compensate for the resistors tolerance. The parallel lines on the proto board allowed for using V_{cc} and ground potential compactly on the proto board; fewer wires were needed for soldering. After soldering the boards, using the potentiometers was a convenient way to adjust the subcarrier frequency to 105 KHz on the transmitter and the capture and lock ranges on the receiver.

Engineering Design and Operation

A description of each of the individual component designs, i.e. PLL or filters, is detailed to include the placement of parts, their purpose, and various testing procedures to verify correct operation.

Input filters

The audio signal is first transmitted through an AC coupling capacitor, C1, that is sized to reject DC bias currents from the LM324 operational amplifier to protect the PC sound card. The resistors, R_5 and R_3 function as a path to ground for these bias currents. A DC offset must be added to the audio signal because ground, i.e. 0 V, is the lowest potential supplied to the transmitter. This is accomplished with R_1 and R_3. The AC coupled audio signal and the DC offset is summed with a voltage summer and fed into the non-inverting terminal of the LM324. The first op-amp stage consists of a voltage follower that prevents distortion of the audio signal by providing a transformation of impedance. The buffered audio signal from the voltage follower was then fed into a second op-amp filter that low pass filters the audio signal to 3 kHz using a second order Butterworth filter with a 3dB cutoff frequency of approximately 4 kHz and a gain of approximately 1.5 which was acquired from a PSpice simulation.

Alongside the PSpice simulation, the input filter stage was tested by using the function generator to input a sine wave with 1 V_{pp}, 0 V DC, a frequency sweep from 1 kHz to 10 kHz, and a sweep time of 5 seconds. The output of the second op-amp is amplified by 1.5 and gradually decreases in amplitude as the frequency increases past the cutoff frequency of the low pass filter.

VCO

A voltage controlled oscillator (VCO) was used to modulate the audio signal ±20% around a sub-carrier frequency of 105 kHz. A VCO is a device that outputs a particular frequency based on what voltage is applied to its control pin. A 555 timer was originally employed to function as a VCO, and to modulate the audio signal. The 555 timer turned out to be difficult to bias within the appropriate ±20% frequency range with the resistor network because the resistance looking into the 555 was not large enough to be approximated by an open circuit. Furthermore, the duty cycle of the 555 changed with applied control voltage which would invalidate the use of the exclusive OR (XOR) phase detector because it requires a 50% duty cycle. For the reasons cited, and also some non-linear effects noticed while working with the 555 VCO, the phase locked loop (PLL) VCO was determined to be superior alternative[2].

The PLL VCO was found to have a duty cycle of 50% consistently, a very high input impedance, and documented procedures in the datasheet to bias the VCO around a center frequency and set the appropriate ±20% bandwidth. The VCO was originally biased by setting the frequency lock range to 84 and 126 kHz (±20%*105 kHz), and then using figures 5, 6, 7 from the CD4046BC data sheet to calculate values for R12 which controls the frequency bandwidth, R11 which controls the frequency offset, and the capacitor value C6. The values for R11 and R12 were then adjusted with potentiometers to yield a voltage range of approximately 1 V that corresponded to a minimum 84 kHz and a maximum 126 kHz. The values for R_{11}, R_{12}, and C_6 were determined to be 18 kΩ, 4.6 kΩ, and 1 nF respectively. The VCO_{in} voltages corresponding to specific frequencies were measured as 1.75, 2.28, 2.78 V to 86, 105, and 125 kHz, respectively. This also applies to biasing the VCO that provides a phase lock on the receiver; however, the frequency is larger at ±40% of the sub-carrier frequency[3].

The input to VCO_{in} is the output of the 1_{st} stage on the transmitter. This is the stage that provides the audio signal DC offset to avoid clipping. The DC offset was set to 2.28 V, and because the audio signal has a maximum of 1.050 V_{pp} the 1_{st} stage will interface with the PLL VCO such that there is a quiescent sub-carrier frequency of 105 kHz, and a frequency bandwidth of approximately ±20%. Interfacing with the 3_{rd} stage, the LED driver, functions well because VCO_{out} is a square wave that has a maximum and minimum value of approximately 6 and 0 V, respectively, which is a large enough voltage to handle the voltage drops across the BJT Q1, and the infrared LEDs D_1, D_2, and D_3. The VCO gain is calculated in Equation 1.

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[2] National Semiconductor. “LM555 Timer” <https://www.cresis.ku.edu/~callen/501/LM555.pdf>

[3] Fairchild Semiconductor “CD4046BC Phase Lock Loop” <https://www.cresis.ku.edu/~callen/501/CD4046BC.pdf>

$$K_v = \frac{\omega_H - \omega_L}{V_{cmax} - V_{cmin}} = \frac{2\pi(125e3 - 86e3)}{2.78 - 1.75} = 237{,}907\ [\frac{radians}{sec * volt}]$$ Equation 1

LEDS

The optical driver at the last stage of the receiver consists of transistor Q_1, three IR LEDs D_1, D_2, D_3, three jumpers, and resistors R_{13}, R_{14}, and R_{15} shown in Figure 3. This section of the receiver is to take the FM square wave signal from the output of the VCO, and transmit it through free space. The LED driver is responsible for turning the IR LEDs ON and OFF at the frequency of the VCO output. The TSAL6100 IR LED with peak wavelength of 940 nm, radiant intensity of 80 $\frac{mW}{sr}$ at 100mA, and an angle of half radiation of ±10° was chosen because of light intensity. The ZTX602 NPN transistor, Q_1, was chosen and biased to operate in cutoff and saturation modes to do the switching task for this section.

The output of the VCO is connected to the base of Q_1 such that when the signal is at a high state, it will push Q_1 to saturation, where the switch is closed. When the signal is at low state Q_1 is in cutoff, where the switch is open. The anode pin of the IR LEDs are connected to V_{cc} through R_{13}, R_{14}, R_{15} so that when Q_1 is ON, sufficient forward bias current (70 mA to 90 mA) will flow through them, and the IR LEDs will emit infrared light. Three headers, with two pins, were added to this design to give options for varying intensity of transmission for short and longer distances. There is only one jumper conducting. That jumper is placed at the 1LED position so the current will flow through R_{15} and D_3 for one IR LED emitting light. Otherwise, to have two or three IR LEDs to emit light, for farther distances, the jumper could be placed in 2LED or 3LED positions.

The optical input section consists of the photodiode D_1, the operational amplifier U_1, and resistors R_1 and R_2 shown in Figure 4. The BP104 with the wavelength of 950 nm was chosen to match the peak wavelength of the transmitter's IR LEDs. The ±65° sensitivity angle of this photodiode makes it a wide electronic eye to see the infrared light coming from the receiver. The output of this photodiode is proportional to the FM square wave that is driving the LEDs on the transmitter side. When D_1 is exposed to the infrared light coming from the transmitter, a forward current is generated flowing in a positive diode direction. This current is very small but the LM318, U_1, and R_2 are used to amplify and convert this current to a voltage level that can drive the demodulator stage.

PLL

The phase lock loop consisted of a CD4046 integrated circuit. A block diagram of the PLL is shown in Figure 6. The modulated input, V_{in}, is received from the infrared detector and is in the form of an approximately 8 V_{pp} square wave with frequency deviation possibly greater than 20%, from the VCO in the transmitter, due to degradation of the transmitted signal over the IRLEDs. The demodulated signal output, V_{out}, is the signal recovered from the modulated wave.

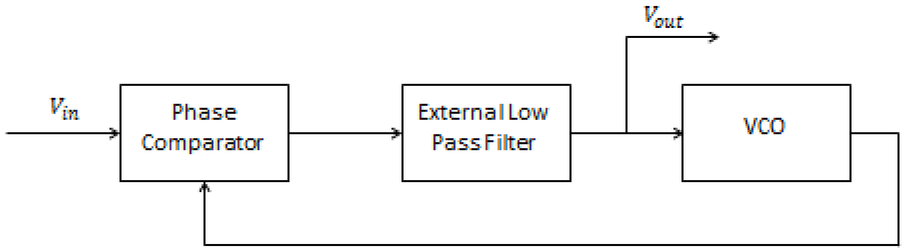

Figure 6: Block diagram of PLL

The PLL operates with a carrier frequency of 105 kHz and frequency deviation of ±40%, from the carrier frequency, set by R_3, R_4, and C_1. Approximate values for R_3, R_4, and C_1 were obtained from the CD4046 datasheet; however, final values that encompassed a ±40% frequency deviation were obtained by testing the VCO individually. The external low pass filter shown in Figure 6 was a passive RC low pass filter with a cutoff frequency of approximately 3 kHz.

To ensure proper operation of the PLL the VCO was tested so that the frequency deviation encompasses the entire range of frequencies that are ±40% from 105 kHz. A low DC voltage was applied to the input of the VCO to set the lower frequency and a high DC voltage was applied to set the higher frequency. The resistances R_3 and R_4 were modified, with C_1 staying constant, to calibrate the upper and lower frequency deviations.

The VCO was then combined with the XOR phase comparator (phase comparator 1) and the external low pass filter. A FM waveform was applied to V_{in} using a function generator modulated by a 1 kHz frequency and 8 V_{pp} sine wave. The output, V_{out} , was viewed with an oscilloscope after the external low pass filter removed the high frequency carrier waveform. If the PLL is locked, V_{out} is a sine wave with 1 kHz frequency and 8 V_{pp}. Figure 8 in the Results illustrates the lock of the PLL by comparing the input modulated waveform and the output of the VCO at steady state, i.e. at carrier frequency (no audio input).

Output filters

The output stage of the receiver functions to filter out any noise higher than 3 kHz which could have come from the PLL during demodulation. This stage is also used to provide any amplification required to drive headphones or speakers with the demodulated audio signal. This stage is configured very similarly to the transmitter input stage. However, the voltage follower is now isolating the rest of the output stage from the other circuitry in the receiver. The LM324, U_3, is only able to source 10-20 mA to drive the audio jack, which was not enough current to drive the headphones to hear an audio signal. A current amplifier was needed to provide the necessary current to drive the audio output. An emitter follower was used to solve this problem because it has current gain with a voltage gain of unity, and is also able to act as a buffer between the audio output and the rest of the receiver circuit. The common-emitter Q_1 is biased with resister R_{10}. The capacitor C_5 is sized such that the outputted signal is based around ground without DC offset.

Results

The frequency capture and lock range of the PLL is shown in Table 1. The frequency capture range is where the PLL locks onto the carrier frequency when the frequency is increased or decreased from a frequency much lower and much higher than the carrier, respectively, until the PLL locks. The lock range is the frequency at which the PLL loses the lock by starting at the carrier frequency and increasing or decreasing the frequency until the lock is lost.

Table 1: Frequency capture and lock range

	Minimum	Maximum
Capture frequency	62 kHz	105 kHz
Lock frequency	15 kHz	141 kHz

An illustration of the phase lock is shown in Figure 7 where the input signal is a sine wave with 1.006 kHz frequency as an input to the transmitter yielding the output of the filter stage in the receiver, before AC coupling. The received is slightly time delayed with a 0.996 kHz frequency in the form on a sine wave due to the attenuation of transmitting the signal over free space. Figure 8 shows an example of the lock by comparing the modulated input to the output of the VCO where the phase angle between the two signals is 90°. In Figure 8, there is no audio input so the VCO on the transmitter modulates the DC voltage provided by the voltage divider, R_1 and R_3, which corresponds to the 105 kHz carrier frequency.

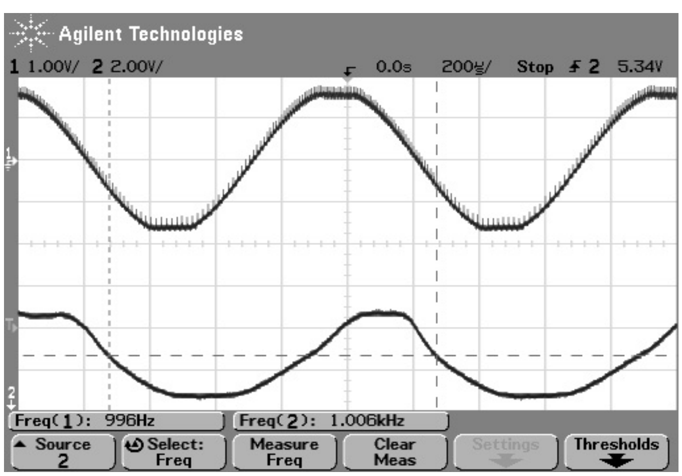

Figure 7: 1 kHz audio input at transmitter (top) with output before AC coupling at receiver (bottom).

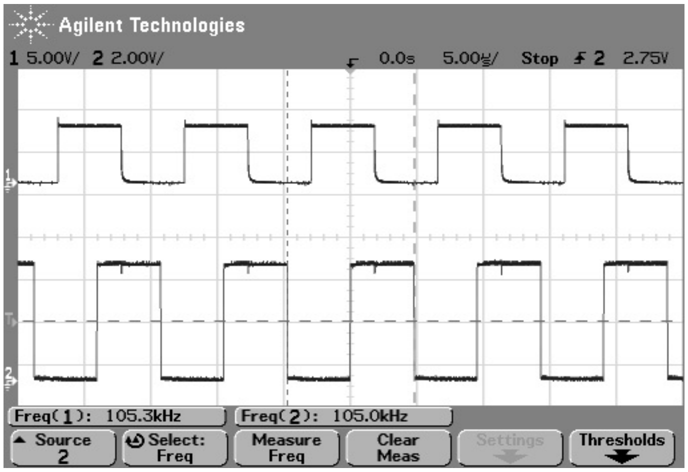

Figure 8: Modulated input (top) and VCO output (bottom), i.e. input to the phase comparator, note the voltage per division for each signal.

The testing setup for both the transmitter and receiver is shown in Figure ??. The supply voltages for the receiver and transmitter are 6 V and 9 V, respectively. The PC in the laboratory is used to supply the transmitter with an audio signal and external desktop computer speakers are used to listen to the audio signal after transmission.

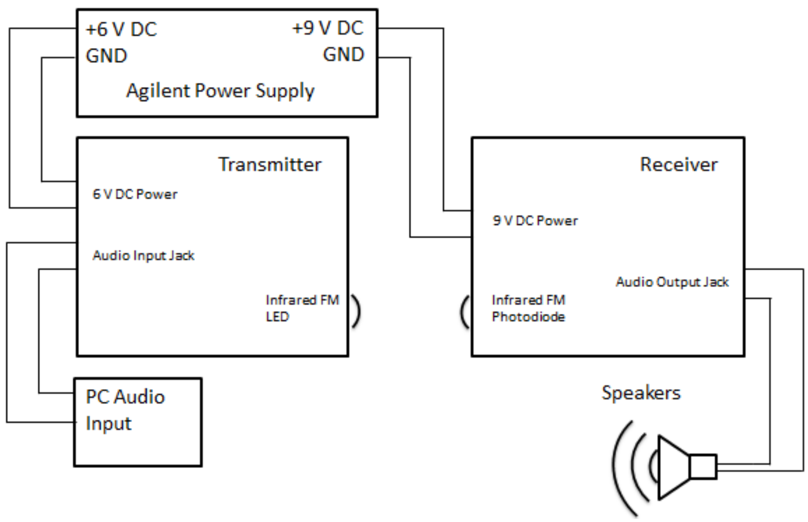

Figure 9: Testing setup for transmitter and receiver

The distances of operation vary with the intensity of the infrared light that is emitted by the LEDs on the transmitter. The maximum distances of operation without significant signal degradation is denoted in Table 2. The number of LEDs that are emitting light is controlled by a single jumper that is shown in Figure 3: Transmitter schematic. Each jumper configuration limits the current through the LEDs to approximately 70 mA, where the maximum current the LEDs can take is 100 mA.

Table 2: Maximum distances for different configurations of IRLEDs

Number of infrared LEDs	Distance [ft]
1	3.4
2	8.5
3	12.1

Conclusion

The infrared FM communication system successfully incorporates audio filters and amplifiers, voltage controlled oscillators, and a phase lock loop to wirelessly communicate an audio signal over free space. The range of frequencies in which the phase lock loop can maintain a lock varies around the sub-carrier frequency of 105 kHz, and the capture range deviates within ±20% and ±40% on the transmitter and receiver, respectively. The FM signal is demodulated, with minimal signal degradation after the 3 kHz low pass filter, at a quality similar to the PC sound card input. The system works within a distance range of 3.4 to 12.1 ft depending on the number of infrared LEDs emitting light.

Recommendations

The note denoted in the MC14046, similar to the CD4046, should be considered when sizing R3, R4, and C1; the equations in the datasheet are strictly a design guide. The VCO, for both the transmitter and receiver should be tuned independent of every other component. The VCO biasing was accomplished without an external resistor network. If the resistor network had been used, a greater control over the frequency to control voltage could have been achieved. Ensuring correct frequency deviation of the VCO would have drastically reduced the time spent on both the modulation and demodulation stages of the project.

An overlook that was encountered during the demonstration was using the internal source follower within the PLL. The circuit that was designed includes an external emitter follower where the output of the PLL was taken from the input to the VCO rather than using the internal source follower. Using the internal source follower would cut down the complexity of the design.