Low Power PLL FM

Transmitter

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ABSTRACT

The Low Power PLL FM Transmitter (LPPFMTx) is a one-way communication system developed for Vinland Motorsports Inc, a local motorsports club. It is to replace the existing method of communication (bullhorn, 2-way radios and/or common FM transmitter) for use during their events, such as auto slalom.

The LPPFMTx is a method of broadcasting announcements (via standard microphone input) tunable by a commercial FM radio, which is not prone to the shortcomings of a common FM transmitter. These shortcomings include high power output and long distance transmissions (which violate government anti-piracy regulations), as well as frequency drifting (caused by factors such as thermal instabilities and inertial forces).

The above problems are avoided via the phase locked loop (PLL) implementation operating in conjunction with an FM transmitter design. The PLL involves the feedback of the FM output, through a frequency divider, to a phase comparator. The signal is then compared against a stable crystal oscillator to produce a variable-duty error signal to be incident upon the voltage-controlled oscillator (VCO). The VCO frequency will then be adjusted until the system reaches equilibrium and is successfully “locked” to that of the stable crystal.

Moreover, the input (voice) signal undergoes high-order Butterworth low-pass filtering in conjunction with power input filtering to maximize the signal-to-noise ratio (SNR) of the system.

The result is a clean and clear FM transmission that has the stability of a crystal and the flexibility of a tunable FM transmitter that can be received on the order of 1 km away and is powered via an automotive accessory (cigarette lighter) jack.

Supervisors: Dr. Weimin Huang
Mr. Andrew Menchions, P. Eng

1 INTRODUCTION

This project, the Low Power PLL FM Transmitter (LPPFMTx), was designed for Vinland Motorsports Inc., as suggested by its Auto Slalom Director, Andrew Menchions. "Vinland Motorsports Inc. (VMI) is an autosport club and a member of Atlantic Region Motor Sport Club (A.R.M.S.), the Canadian Association of Rallysport (C.A.R.S.) and affiliated with ASN-Canada-FIA. VMI organizes rallies and auto slalom events throughout the year and aims to promote all aspects of autosport in the Province of Newfoundland and Labrador".[1]

The purpose of the LPPFMTx is to replace the existing rudimentary communication system with a more sophisticated system available to all participants and competitors.

1.1 Auto Slalom Background

Auto Slalom is a motorsports event similar to the American "autocross". "An autocross is a timed competition where drivers navigate one at a time through a temporary course marked by traffic cones, rather than racing on a track with multiple other cars, as in road racing or oval racing. Autocross tends to place more emphasis on car handling and driver skill than on sheer horsepower, and events typically have many classes which allow almost any vehicle, from economy sedans to purpose-built vehicles, to compete. Speeds are slower in absolute terms when compared to other forms of motorsports, usually not exceeding highway speeds, but the activity level (measured in driver inputs per second) can be higher than even Formula One due to the large number of elements packed into each course.”[2]

1.2 Current Communication Setup

The current communication setup employed by VMI includes the following:

- Photogates
- Controller & Stopwatch
- Bullhorn / Common FM Transmitter

1.2.1 Photogates

There are two photogates being utilized by the current communication setup – at the start gate and stop box. These are triggered when the currently competing car crosses the plane between the transmitter and receiver.

1.2.2 Controller & Stopwatch

When the first photogate is triggered, the controller activates the stopwatch and similarly deactivates it upon the triggering of the second photogate. The resulting time is then recorded in a spreadsheet either manually or on a laptop in the timing vehicle.

1.2.3 Bullhorn / Common FM Transmitter

A bullhorn or common FM transmitter may or may not be used to relay run times and other announcements. The main purpose of the LPPFMTx is to replace this element of the current communication setup. When referring to a "common FM transmitter" in this document, the reference is to any that will cost around $20 and operate in open loop.

2 SYSTEM DESIGN

The Low Power PLL FM Transmitter System can be superficially broken down into the components illustrated in Figure 1.

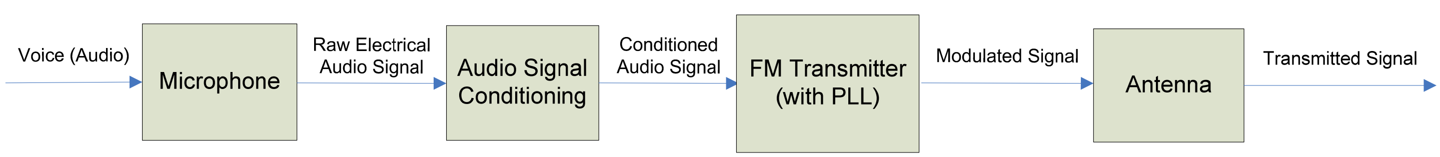

Figure 1 Low Power PLL FM Transmitter Block Diagram

For design, and subsequent analysis, it is more appropriate to consider the system using the following modules and sub-modules:

- Audio Module
    - Microphone
    - Audio Signal Conditioning
- Phase-Locked Loop (PLL) Module
    - Crystal Oscillator

    - Voltage-Controlled Oscillator
    - Frequency Divider
    - Phase Detector
    - Loop Filter
- FM Transmitter
    - FM Modulator
    - RF Amplifier
    - Antenna
    - Channel Selection

The physical layout of these modules is illustrated in Figure 2. The modules will be broken down and subsequently discussed throughout this document.

External connectors include:

- 3.5mm jack – microphone input
- Rocker switch – power on/off
- LED – power indicator
- Power jack – power from 12V adapter
- Push button – channel selection
- 4 x LED – channel indicator
- BNC-style connector – Antenna output

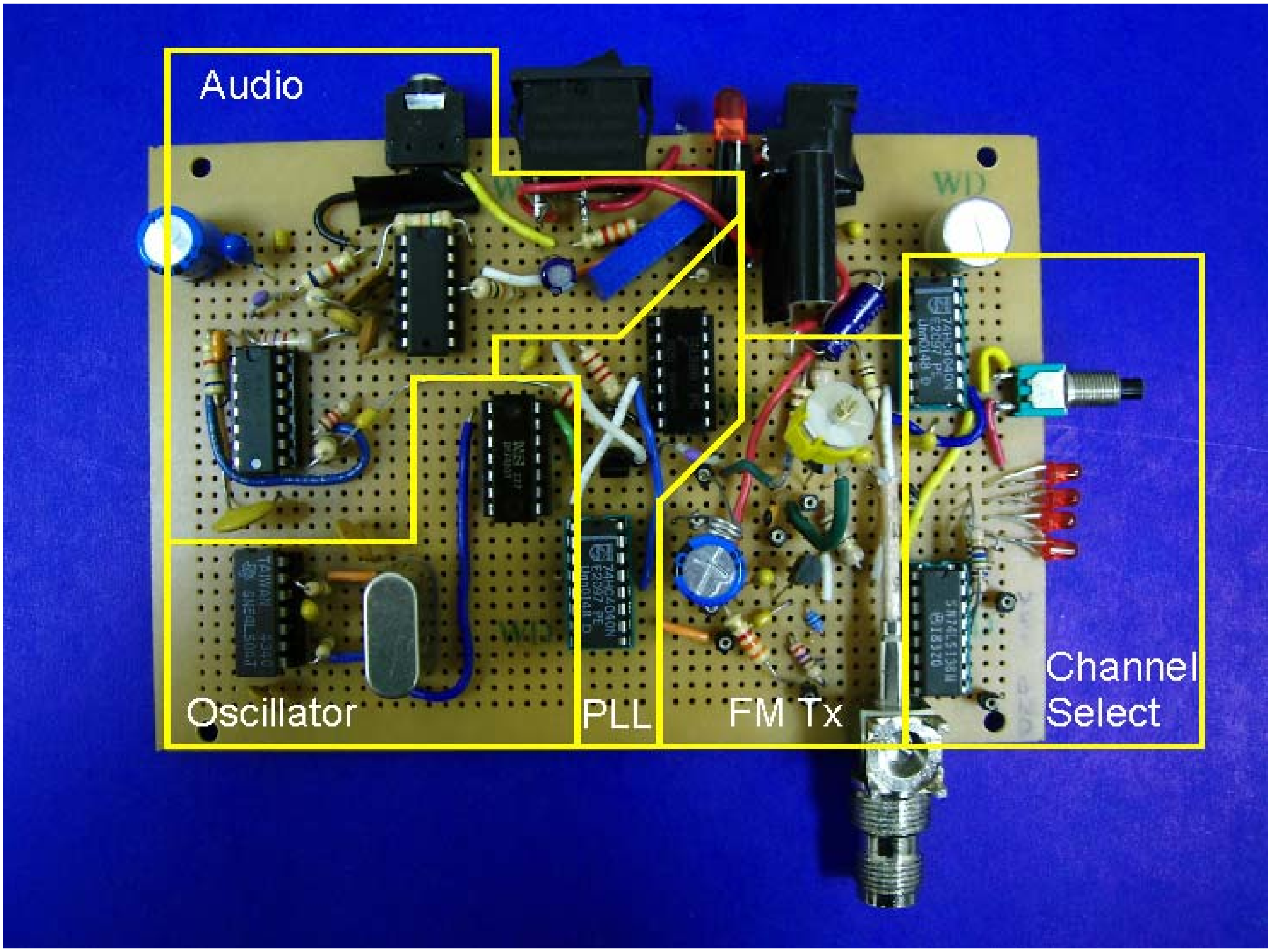

Figure 2 LPPFMTx Board with Outlined Modules

2.1 Audio Module

The audio module is the first stage of the LPPFMTx that converts a voice audio signal to a usable electrical signal. The sub-modules are described in the following sections.

2.1.1 Microphone

The microphone component of the system has one simple requirement – quality. If the microphone is low quality, then attenuation and distortion may occur to such a degree that the resulting signal may be unrecoverable or unusable even before it undergoes any processing [3].

The specifications of the chosen microphone (Labtec Mono 341 headset, shown in Figure 3) are as follows:

- -38 dBV/Pa ±4dB sensitivity
- 100-16,000 Hz frequency response
- 8' shielded cord with gold-plated 3.5mm color coded jacks

Figure 3 Microphone (Labtec Mono 341 Headset) [4]

Before the audio can undergo any conditioning, the microphone must undergo biasing – a dc excitation current must be applied to the internal crystal of the microphone in order for it to convert the audio to an electrical signal (here forth this electrical signal will be referred to as "audio") [5]. The resultant offset ac signal must then be decoupled in order to retrieve the pure audio signal. Simply put, you must put dc on to get ac off. The microphone biasing circuit is shown in the audio conditioning circuit diagram, Figure 4.

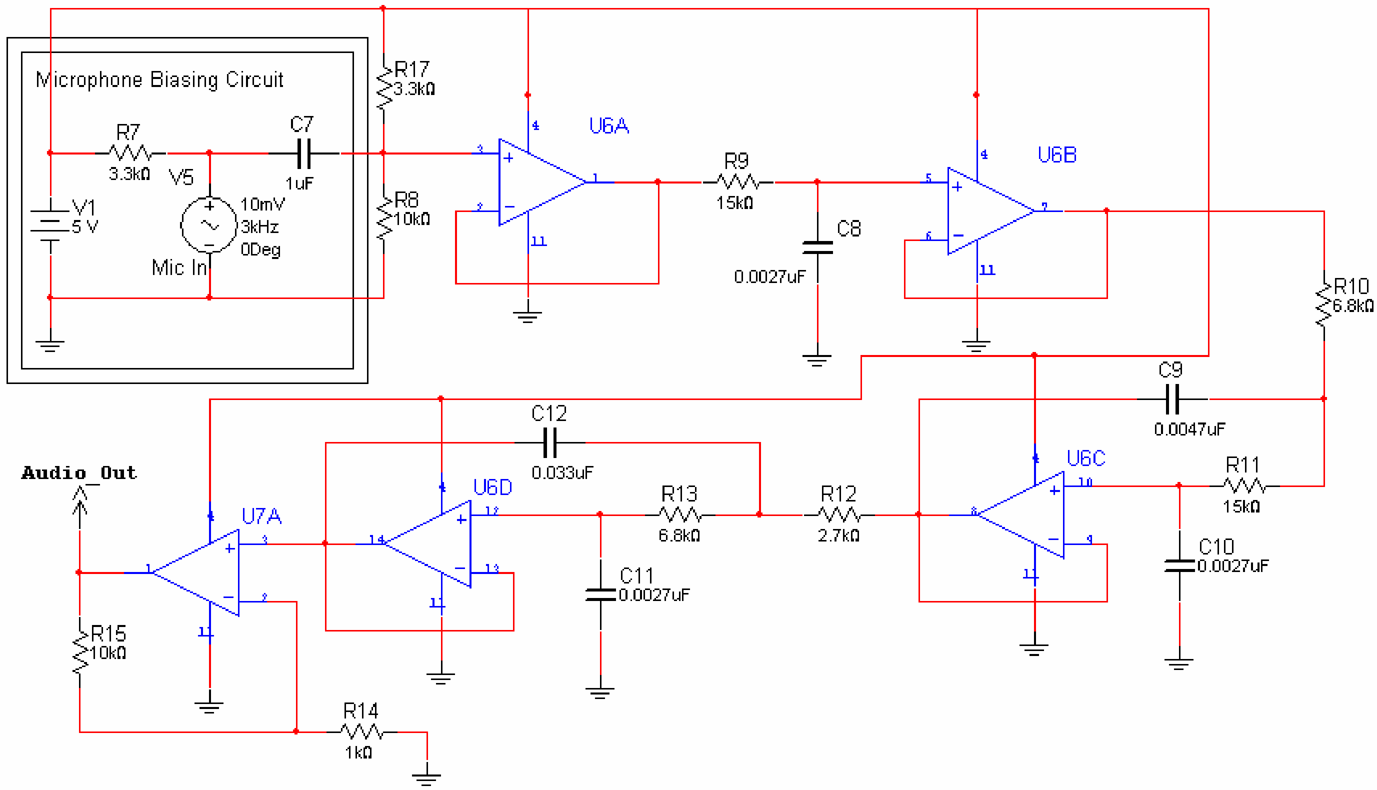

Figure 4 Audio Signal Conditioning Circuit

2.1.2 Audio Signal Conditioning

Once the audio signal has been decoupled, it is buffered by U6A (an LM324 single supply op-amp) so that the biasing circuit does not affect the resonance of the filter. After buffering, the audio undergoes 5th order Butterworth low-pass filtering (U6B through U7A) with an algebraic gain of 11 V/V (21 dB). The range of human hearing is normally defined as 20-20,000 Hz [6]; however, since the LPPFMTx system is designed as a vocal transmitter, the filter was designed to accommodate voice signals only (100-4000 Hz). The filter was designed using

FilterLab by Microchip Technology Inc. The magnitude frequency response is shown in Figure 5.

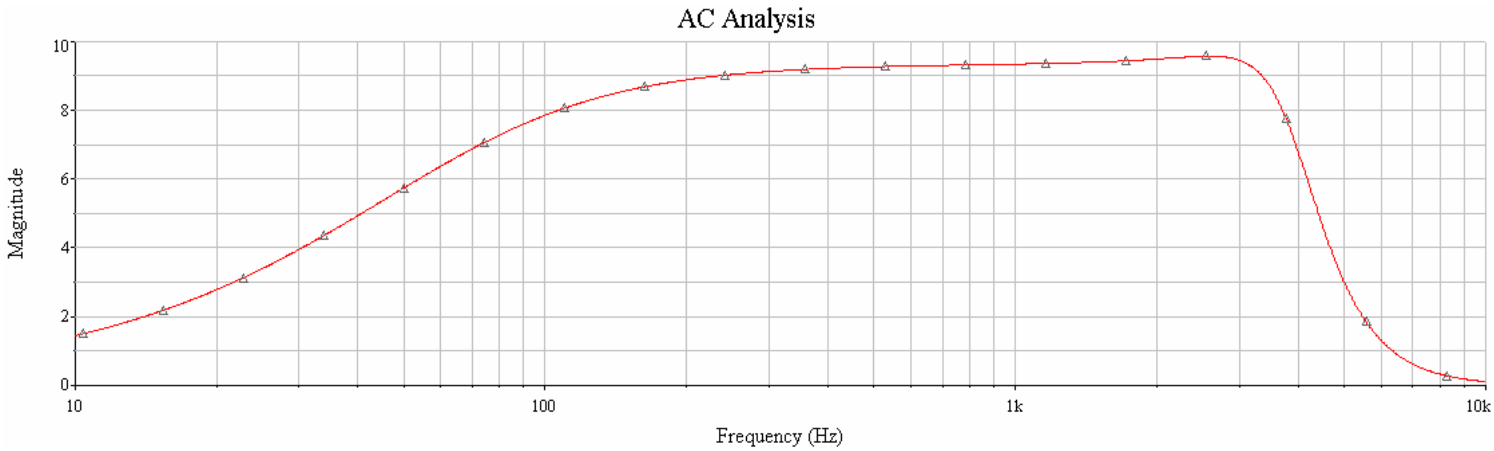

Figure 5 Magnitude Frequency Response of Audio Conditioning Circuit

The LM324 is the op-amp IC of choice because it can operate on a single supply, making it appropriate for this application, as a car battery is the ultimate power source. The input signal of the first op-amp requires a slight dc offset such that it can simulate its negative half-cycle above ground.

The physical layout of the audio module is shown to the right in Figure 6.

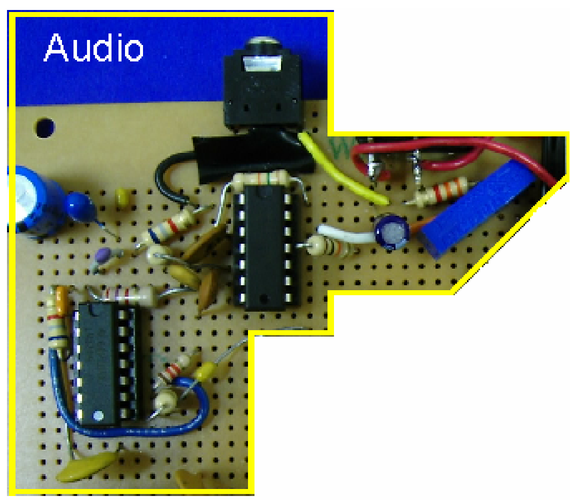

Figure 6 Audio Module Circuit Layout

2.2 Phase-Locked Loop Module

"A phase-locked loop (PLL) is a closed-loop feedback control system that maintains a generated signal in a fixed phase relationship to a reference signal." [7]

The PLL subsystem is to counteract the main impracticality of using a cheap, commercial FM transmitter for this application. Namely, using a simple, transistor-based oscillator will result in a drift in frequency. This may be due to inherent instabilities in the oscillator, load-induced instabilities in the power rails, thermally-induced instabilities, inertial forces, etc. Frequency drifting will cause problems in reception forcing the person at the receiving end to retune the receiver (in this case, the car or hand-held radio).

The block diagram for a PLL is shown below in Figure 7.

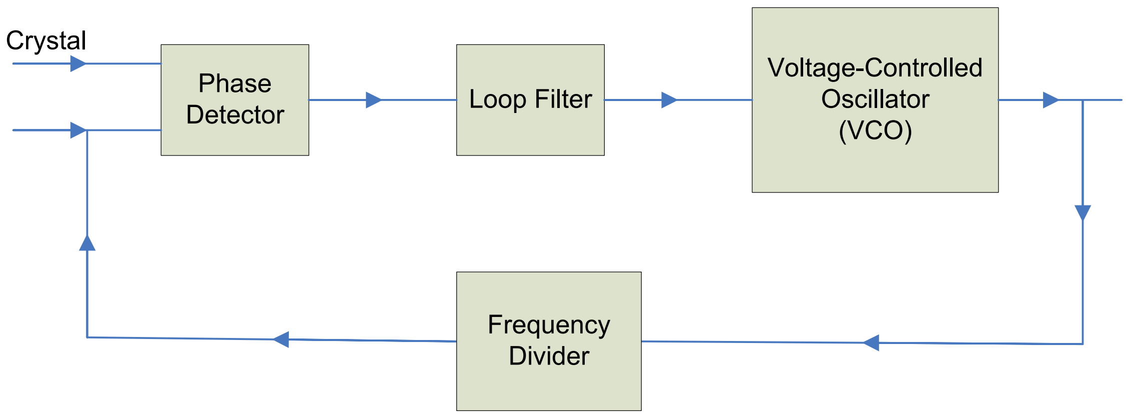

Figure 7 Phase Locked Loop (PLL) Block Diagram

Each block in the previous figure will be described in the following sections.

2.2.1 Crystal Oscillator

The crystal oscillator is an essential component of a PLL system – it contributes the stability that is required to overcome the shortcomings of a common FM transmitter.

The crystal is excited by simulating negative resistance using an RC circuit in conjunction with inverters, as shown in Figure 8. Upon power-up one of the inverters will be forced high and start the oscillation process – the crystal will proceed to oscillate at its natural resonant frequency.

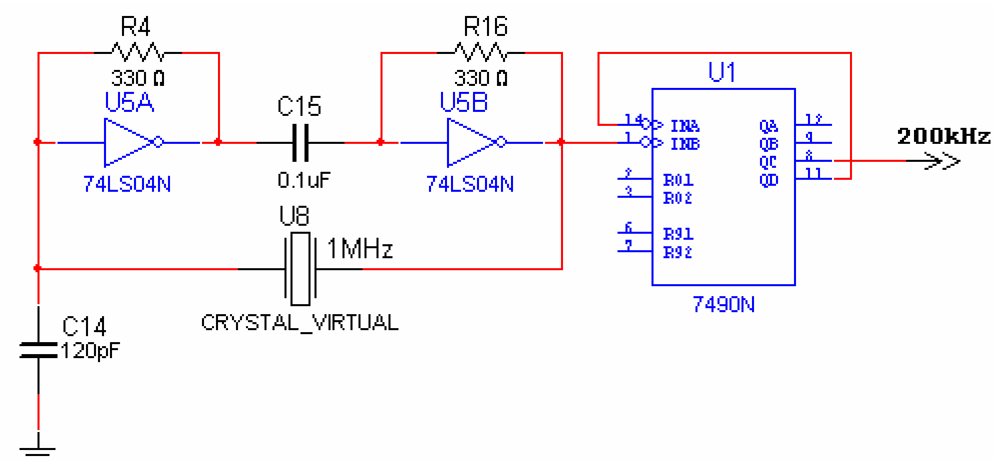

Figure 8 Crystal Oscillator Circuit Diagram [8]

The crystal integrated into the LPPFMTx system is a 1 MHz oscillator. However, since the crystal will determine the resolution of the tuning ability of the PLL, it is desired to convert it to 200 kHz (the transition band between commercial radio stations).

The frequency is divided using a DM7490N Bi-quinary counter (in divide-by-5 mode) to provide a highly stable 200 kHz square wave as shown in Figure 9.

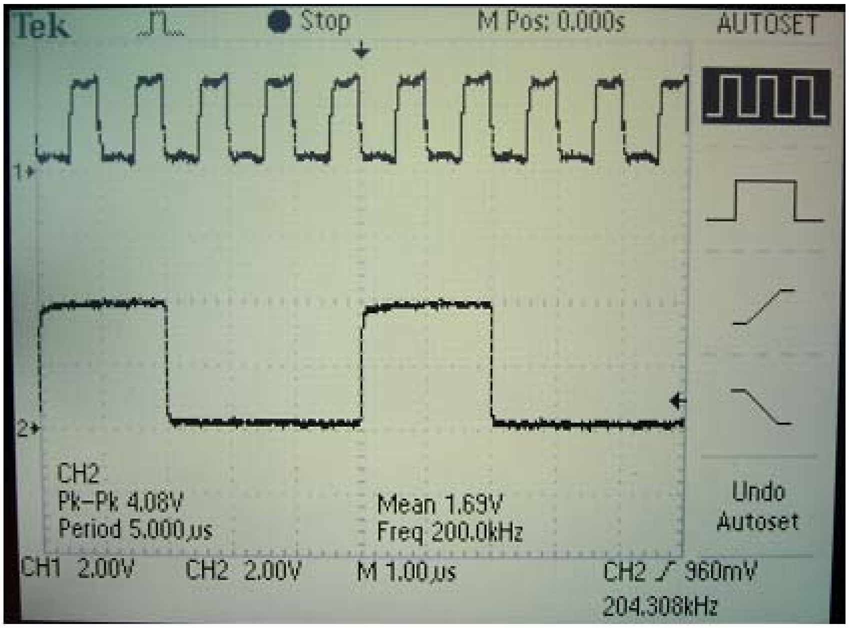

Figure 9 200 kHz square wave from 1 MHz crystal

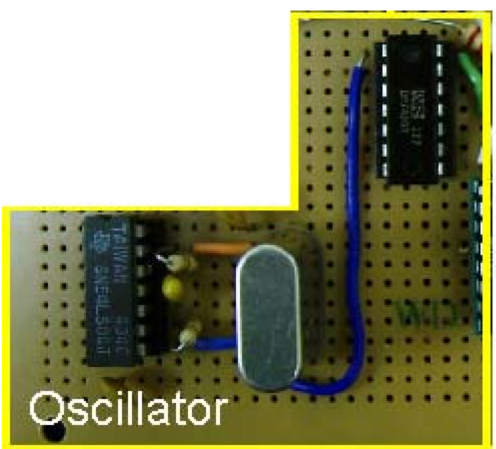

Figure 10 Oscillator Module Circuit Layout

This square wave acts as a parametric input to the PLL circuit (namely, the phase detector).

The physical layout of the oscillator circuit is shown in Figure 10.

A crystal cannot (or should not) simply be used as a solution to the stability issue associated with a common FM transmitter because it cannot be tuned to resonate at a frequency other than its fundamental.

2.2.2 Voltage-Controlled Oscillator (VCO)

Due to the cyclic nature of the PLL process, its performance is perhaps best analyzed by starting at the output and working backwards to the "input". The most obvious point to consider as the output would be the VCO.

The basis of the VCO is to accept an error voltage from the preceding PLL components and adjust its resonant frequency appropriately. The error voltage is incident upon a varactor, D_1, (MV2101) which acts as a voltage-controlled capacitor (naturally), therefore changing the resonance. The VCO schematic is shown in Figure 11.

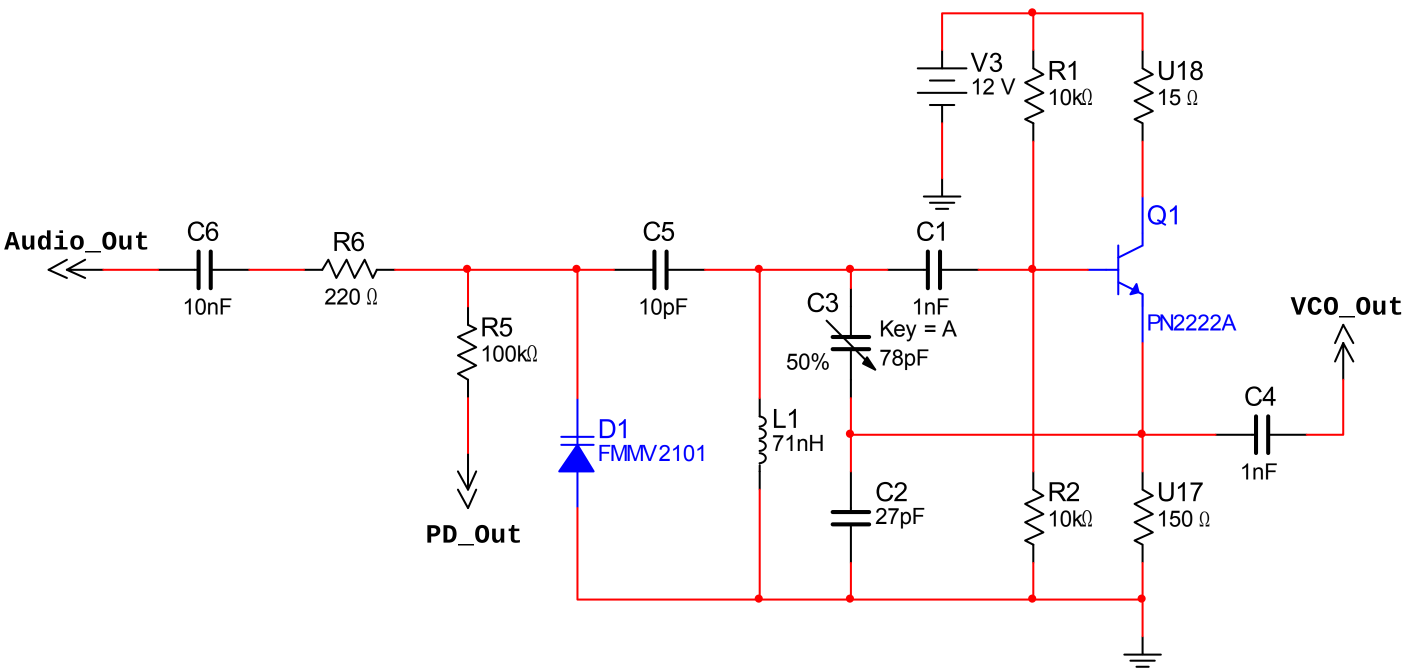

Figure 11 VCO / FM Modulator Schematic

The oscillator is based around a general purpose PN2222A NPN bipolar transistor which is configured as a Colpitts oscillator. Without the varactor (and its associated input) the oscillator would operate open-loop as a common FM transmitter. With the varactor, the frequency of oscillation is defined by Equation 1.

$$f = \frac{1}{2\pi\sqrt{L_1\left(\frac{D_1 C_5}{D_1 + C_5} + \frac{C_2 C_3}{C_2 + C_3}\right)}}$$

Equation 1 Resonant Frequency

It is easily observable that any change in the capacitance of the varactor, D_1, will result in an alteration of the resonant frequency. Moreover, the variable capacitor, C_3, can be adjusted to tune the VCO as a system that ranges from 88-108 MHz (bandwidth of commercial radio), depending on the input to the varactor. The inductor was 2 turns of 22 gauge wire.

2.2.3 Frequency Divider

The output of the VCO* is fed back to a 74HC4040 high speed 12-stage binary counter, which acts as a frequency divider. The PLL feedback loop schematic is shown in Figure 12.

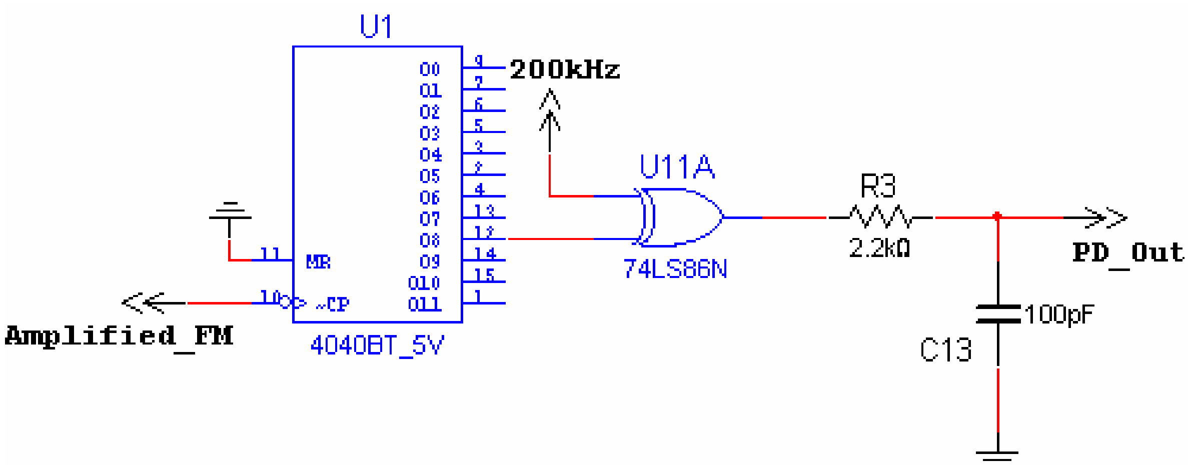

Figure 12 PLL Feedback Loop Schematic (Frequency Divider, Phase Detector & Loop Filter

By selecting output Q8 of the counter, the input FM signal is effectively divided by 512. Since the original signal is on the order of 100 MHz, the quotient is on the

*Actually, the output is from the RF amplifier, because the VCO signal output has a magnitude too low to trigger the clock of the counter IC. However, the premise is the same.

order of 200 kHz – the proximity of the reference signal implemented by the crystal oscillator circuitry.

2.2.4 Phase Detector

The purpose of the phase detector is to quantify the difference in frequency and/or phase of any two input signals. In this case, a simple exclusive OR gate [9], U11A (74LS86) in Figure 12, was utilized to generate the error signal.

As shown in Figure 13, the yellow square wave represents the frequency-divided version of the FM signal, the cyan square wave represents the divided crystal oscillation and the magenta waveform is the error signal generated by the phase detector.

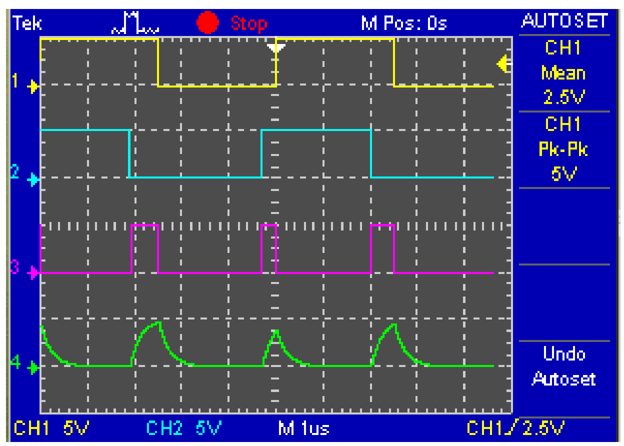

Figure 13 Phase Detector & Loop Filter Waveforms

This error signal is a variable-duty square wave that is based on the diversity of the two inputs.

2.2.5 Loop Filter

The structure of the loop filter is equivalent to that of a first order low-pass filter. However, its purpose is actually to average (i.e. smooth) the error signal generated by the phase detector, shown as the green waveform in Figure 13.

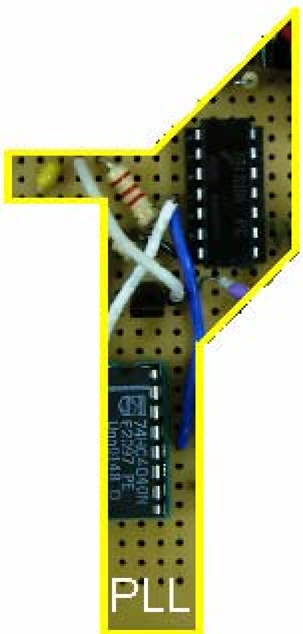

Figure 14 PLL Feedback Loop Layout

The cutoff frequency is chosen at an arbitrary multiple of the operating frequency of the phase detector to ensure its proper operation (in this case 723 kHz). The averaging causes the capacitor to charge or discharge, as necessary, against the varactor to adjust the VCO. This process continues until the error signal has a zero duty cycle and the VCO is effectively "locked" to the frequency of the crystal-based oscillator.

The physical layout of the PLL feedback loop is shown in Figure 14.

2.3 FM Transmitter Module

Figure 15 FM Transmitter Layout

The FM transmitter module carries out the FM modulation, amplification and transmission of the conditioned audio signal.

Its physical layout is displayed in Figure 15.

2.3.1 FM Modulator

The FM modulator is based around the PN2222A bipolar transistor [11] in conjunction with the VCO shown in Figure 16.

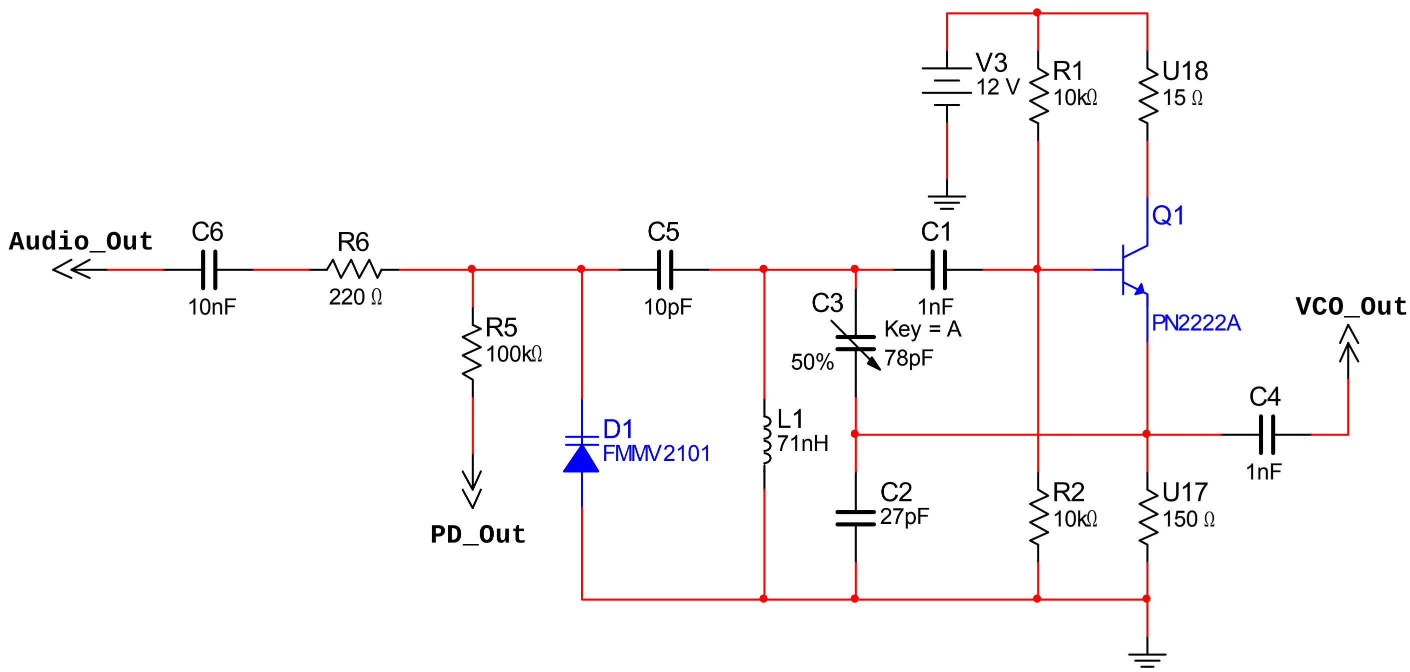

Figure 16 VCO / FM Modulator Schematic†

The audio signal is incident on the base of the transistor and causes it to switch at the instantaneous frequency of the audio. The base-emitter junction is oscillating at the frequency controlled by the VCO, resulting in the output at the emitter to be a frequency signal switched at *another* frequency – this is the frequency modulation (FM). A snapshot of the resultant output can be seen in Figure 17.

† Figure 11 re-inserted as Figure 16 for local clarity.

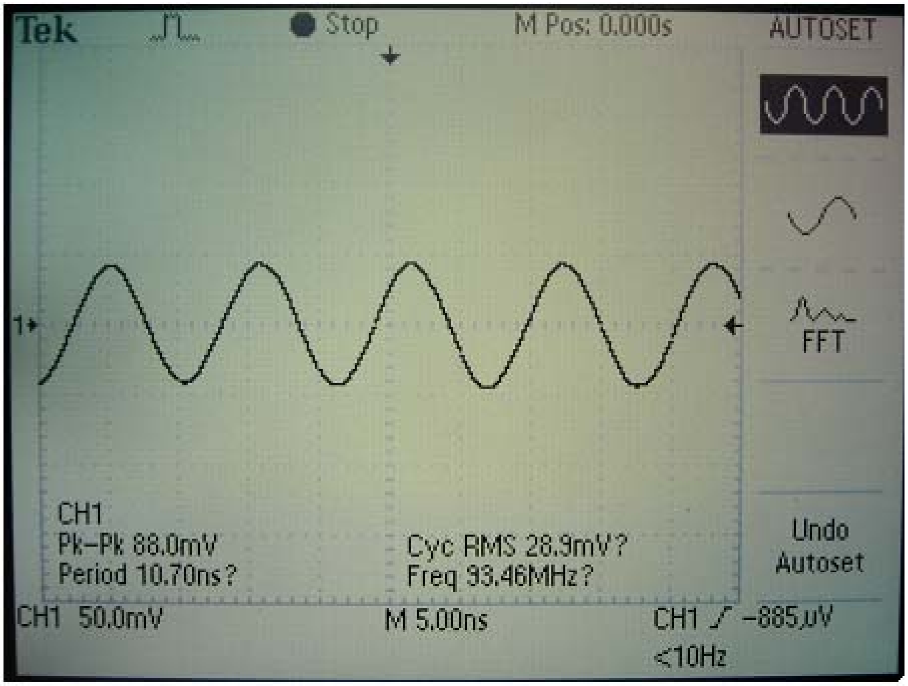

Figure 17 Sample FM signal @ 93.5 MHz

Tuning the first (inherent) stage of power amplification is done via the collector resistance (U18) and the emitter resistance (U17) – both are ½ watt resistors. Decreasing U18 will result in a higher voltage output. Decreasing U17, while decreasing the voltage output, will increase the current and result in a net higher power output.

2.3.2 Radio Frequency (RF) Amplifier

The FM signal from the modulator is amplified by an appropriate gain to obtain the desired level. The RF amplifier is based around a 2N3819 N-Channel JFET and its schematic is shown in Figure 18.

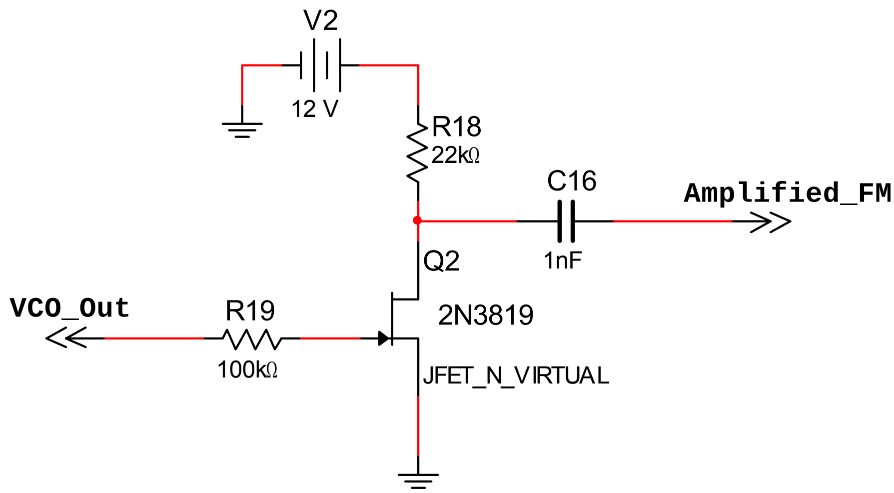

Figure 18 RF Amplifier Schematic

The 2N3819 typically operates up to 450 MHz; therefore, stable amplification is easily attained on the order of 100 MHz.

Sample waveforms are shown in Figure 19. The yellow waveform is a sample FM signal from the VCO and the cyan waveform is the amplified FM signal from the RF amplifier.

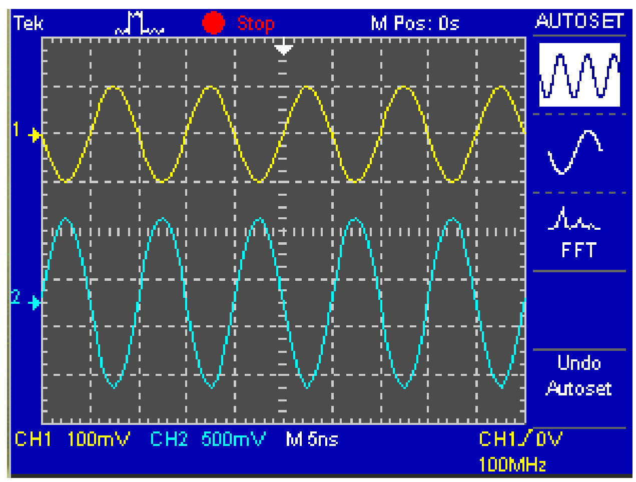

Figure 19 FM Waveforms

2.3.3 Antenna

Any selection of antenna is based on the wavelength of the signal it will typically be transmitting (or receiving). Considering air as a fair approximation of free space, the wavelength, λ, can be determined using equation 2.

$$\lambda = \frac{c}{f}$$

Equation 2 Wavelength Calculation

Where,

- c is the speed of light in a vacuum ≡ 3×10^8 m/s.
- f is the frequency of the signal – on the order of 100 MHz.

Using these values yields a wavelength of 3m.

This would be the ideal wavelength to utilize when calculating the length of antenna to transmit the signal. However, when dealing with broadcasting, the mechanical length becomes slightly less important (the importance of length being predominant in directional transmissions). Therefore, the availability of a 2.4 GHz wireless router antenna was proposed as the LPPFMTx antenna.

In consideration, this antenna was modelled in Matlab to observe its characteristics. The results can be seen in Figure 20.

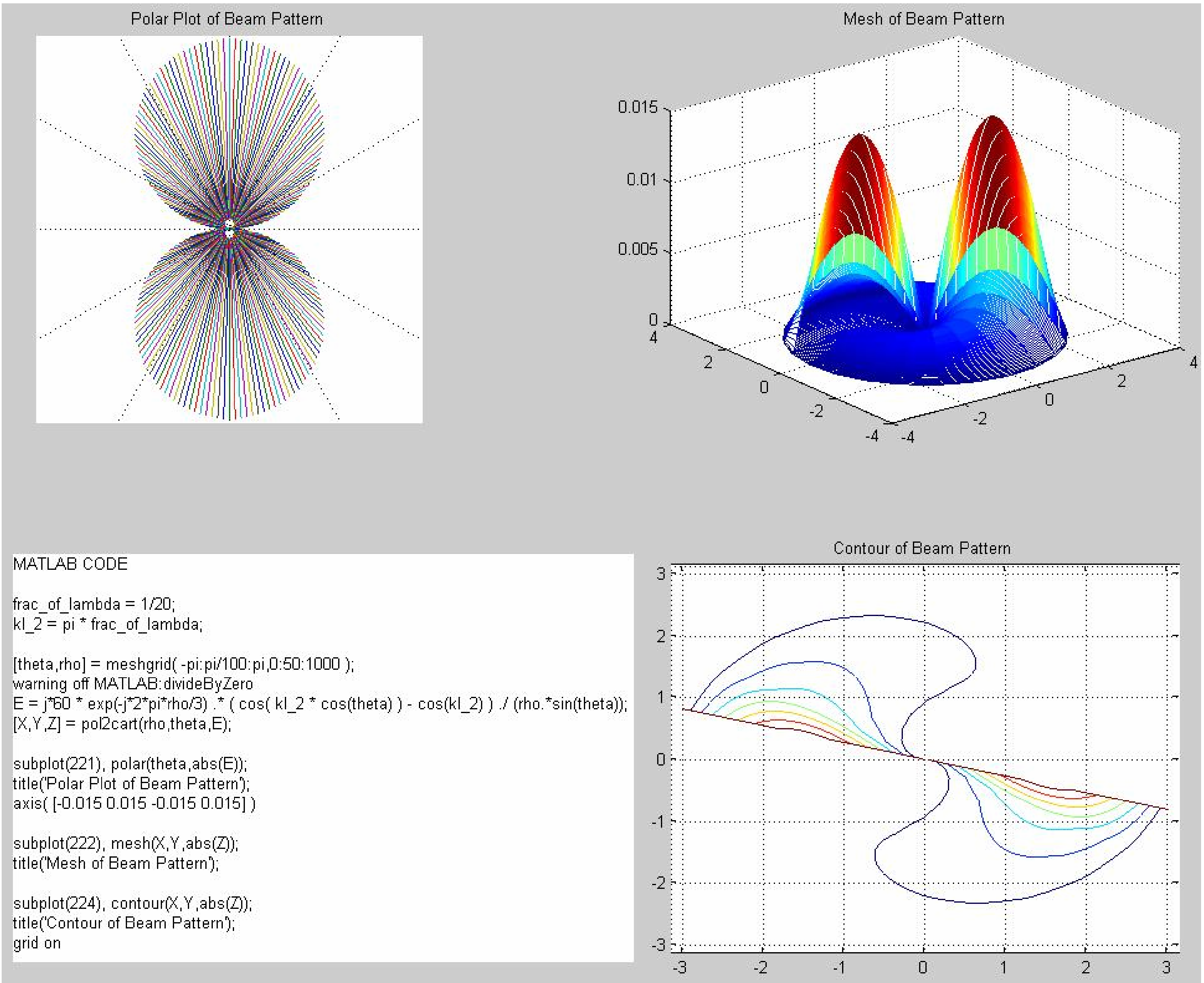

Figure 20 Matlab Antenna Modeling (& Code)

The antenna electrical field pattern characteristics were based on equation 3 [11].

$$\vec{E}(\vec{r}) = E_\theta \hat{\theta} = \frac{j\eta I_0 e^{-jkr}}{2\pi r}\left[\frac{\cos(\frac{kl}{2}\cos\theta) - \cos(\frac{kl}{2})}{\sin\theta}\right]\hat{\theta}$$

Equation 3 Antenna Electrical Field Pattern

It can be observed from the antenna characteristic plots that this antenna is suitable for broadcast on the order of 100 MHz (as a $\lambda/20$ monopole) despite being designed for 2.4 GHz. Moreover, its compact size is more desirable than an antenna on the order of metres.

2.3.4 Channel Selection

The template for channel selection is set up such that, by pushing a normally-open button, the channel will cycle between four pre-determined values. Moreover, an LED will indicate the active channel.

The setup involves the de-bounced button to act as a clock input to the counter which will address a 74LS138 decoder/demultiplexer. The active-low outputs of the decoder will determine which channel is active. This is illustrated in Figure 21.

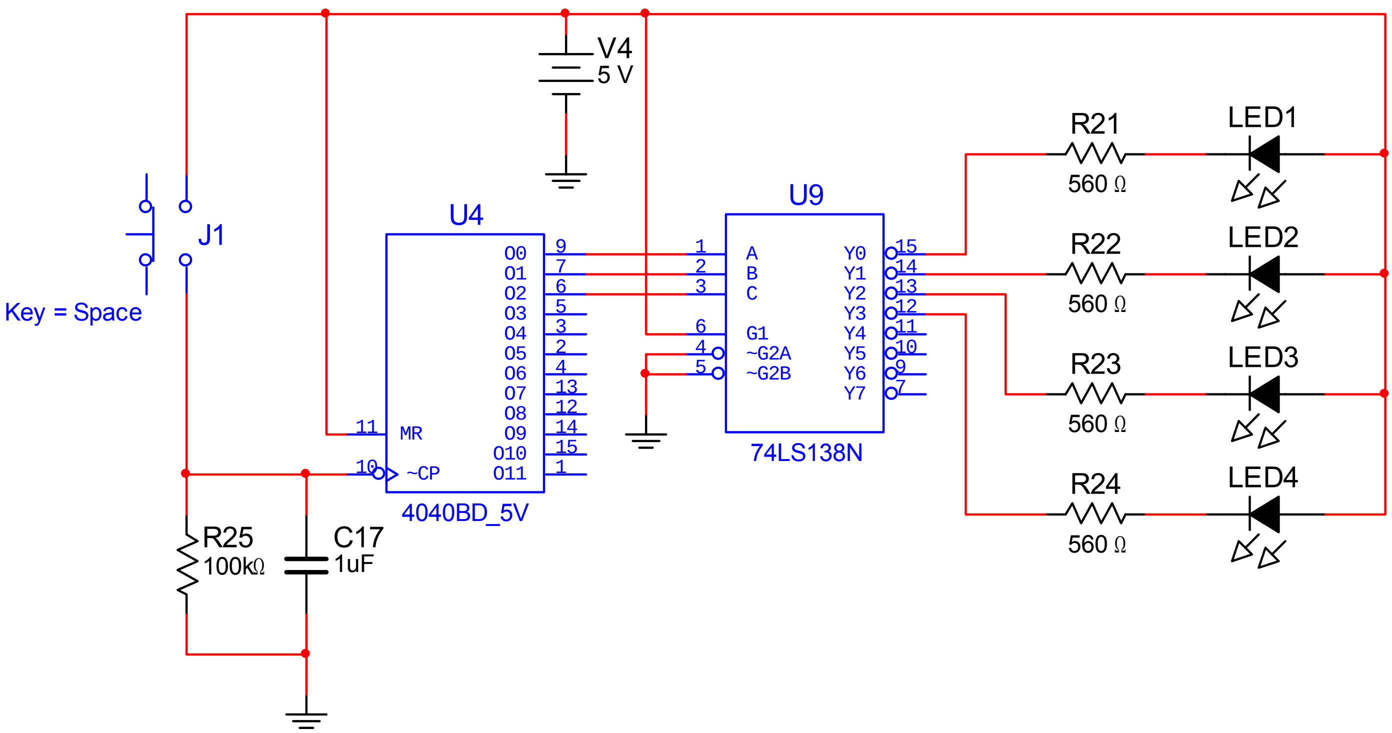

Figure 21 Channel Selection Schematic

2.4 Auxiliary Components

External to the LPPFMTx circuit board, the following auxiliary components were utilized:

- Microphone headset
- 12 V accessory car power adapter
- 12 V accessory car jack
- 12 V battery
- Antenna

These components can be seen in Figure 22.

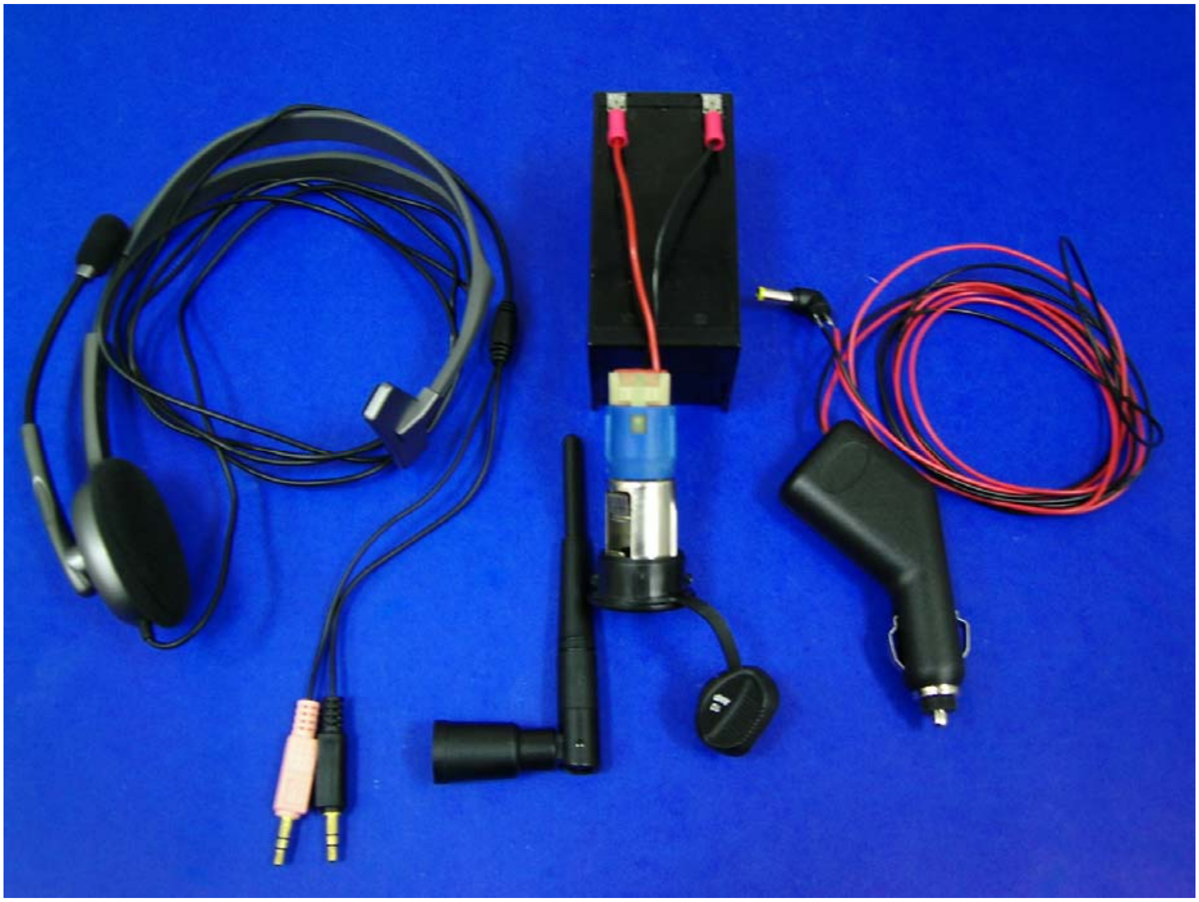

Figure 22 Auxiliary Components

The microphone and antenna were discussed in sections 2.1.1 and 2.3.3, respectively.

The 12 V power adapter circuitry is replaced with onboard 12V regulation, where necessary, the cabling is replaced with longer wiring and a custom connector is attached to be compatible with the LPPFMTx.

The 12V battery and accessory jack were used to simulate the intended power source – a car battery.

3 RESULTS AND RECOMMENDATIONS

3.1 Performance Results

The audio module produces a noise-free voice signal that was tested for clarity on quality-controlled speakers.

The FM output signal produced by the modulator in conjunction with the PLL implementation is highly stable and carrying clean audio. Moreover, the system possesses the tuneability of a common FM transmitter while maintaining crystal stability.

The second stage RF amplifier allows for the adjustment of gain, such that the desired broadcast radius can be achieved.

FM is broadcast at 115 mW – within the desired spec, such that it does not impinge on government broadcast limitation laws (<1W). Current consumption is 84 mA – most of which can undoubtedly be attributed to the 7805 voltage regulator.

3.2 Problems / Implementation Issues

3.2.1 Microphone Biasing

Implementing the correct biasing network to extract audio from the microphone was a preliminary issue. Slow iteration revealed the proper bias point without damaging the internal crystal.

3.2.2 Immeasurable Inductance

Measuring the inductance of custom wound inductors proved non-trivial. After successive iterations of unwinding, without actual reduction in inductance yielded the discovery that the in-house LCR meter could not measure below an order of μH (the inductance of the cabling was about 1.5 μH), while the orders of the inductors in question were nH. As the highest quality piece of equipment, the Tektronix oscilloscope was the basis of the design of a custom inductance (or, more generally, reactance) meter. The design is shown in Figure 23.

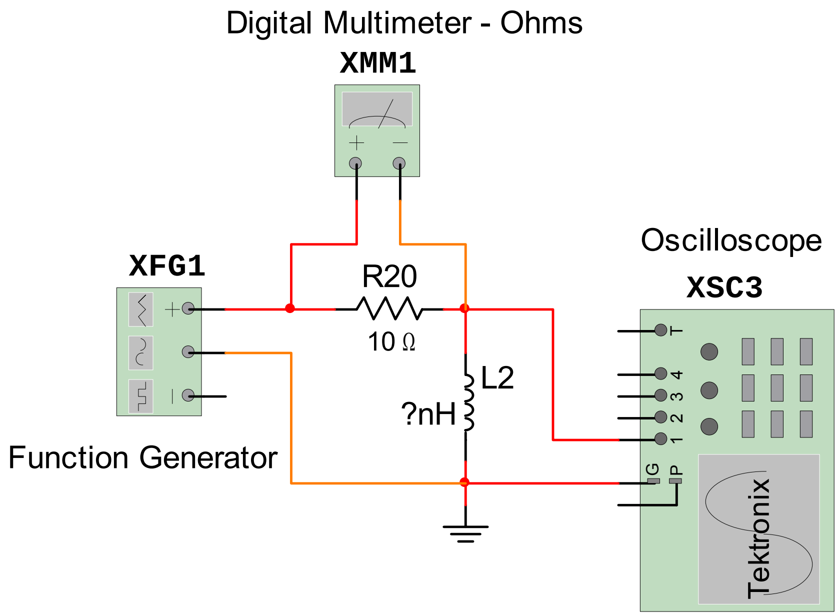

Figure 23 Custom Inductance Meter

By choosing a low, 10 Ω, accurately measured (by the DMM/ohmmeter) resistor, voltage could be maximally divided such that the voltage across the inductor could be accurately measured by the oscilloscope. By applying an accurately measured 1V pulse to the resistor, the inductance could be determined by equation 4.

$$L = \frac{V_L R}{2\pi f(1 - V_L)}$$

Equation 4 Inductance Meter Calculation

Where V_L is the voltage measured by the oscilloscope across the inductor.

3.2.3 Frequency Division

The frequency divider (one of the main PLL components) first introduced difficulties whereby the ICs chosen to perform the task were unable to function at a frequency on the order of 100 MHz. Various implementations of 74LS series frequency dividers, counters, flip flops and timers failed. The solution to the clock frequency issue was resolved with the special order of the 74HC series (high speed) 12 stage binary counter.

However, further issue arose due to the fact that the output FM signal from the VCO had a magnitude too low to trigger the counter as an edge of the clock (requiring a minimum of 2.4 V). This was resolved with the implementation of the RF amplifier, which was necessary regardless.

3.2.4 RF Infection

Due to a freak accident while changing batteries, a current spike, which caused the fuse to be blown, entered the LPPFMTx board. At best, some of the power rail filtration was damaged causing the power rail and/or ground plane to be infected with RF energy (due to acting as a receiving antenna of the FM transmission).

Due to the fact that the ground plane was at a potential of 100 mV and oscillating at a frequency on the order of 100 MHz, the audio conditioning could no longer function properly. This was a result of the fact that the output of the microphone, before conditioning, is on the order of 5-10 mV. Therefore, when referenced to a 100 mV, 100 MHz ground plane, resulted in a lack of any remaining coherent signal to be transmitted.

However, the FM transmitter module remained functional and could continue to transmit, for example, tones from a function generator input directly to the base of the first stage transistor.

Unfortunately, this issue could not be resolved before the project demo and will remain unresolved until after graduation.

3.2.5 Recommended Design Improvements

To reduce the amount of RF infection within the circuit, the following methods could be employed:

- Optocouplers/isolators – by optically isolating the RF and low frequency (LF) portions of the circuit board, physical ground continuity can be avoided and therefore, ground infection would not pose a problem to the LF circuitry.

- PCB board development – by developing the LPPFMTx circuit on a printed circuit board, RF infection can be reduced due to the shorter traces required to connect circuit components. Moreover, microstrips allow for a more versatile matching network development between amplifiers, the input (LF circuitry) and output (antenna).

- Toroidal cabling could be implemented at any transition between LF and RF circuitry. This will confine any electric fields to within the toroid and prevent and infection or leakage to other parts of the circuit.

To properly manage selecting between broadcast channels, one of the following methods may be employed:

- Continuous Inductor Deformation – by attaching a deformable inductor to a rotary knob, the resonance of the FM modulator can be adjusted. This happens because the length of the inductor changes which causes the inductance to change according to the relationship described in equation 5.

$$L(\mu H) = \frac{d^2 N^2}{18d + 40z}$$

Equation 5 Wheeler's Inductance Equation [12]

Where, d is the diameter, z is the length (both in inches) and N is the number of turns.

- Discrete PWM/Varactor – by applying a PWM (possibly from a microcontroller) to a varactor operating within the tuning paramaters of the FM modulator, one can utilize its voltage-controlled capacitance to adjust the resonance of oscillation, by varying the PWM duty cycle. Moreover, the existence of a microcontroller lends itself to the possible inclusion of an LCD display that can display parameters such as the current broadcast station.

4 RESOURCES COST ANALYSIS

4.1 Parts List Costing

The table below outlines the components/parts utilized in the construction of the LPPFMTx‡.

Part #	Description	Unit Cost	Quantity	Gross Cost
SJ1-3545N	3.5mm jack	$0.71	1	$0.71
PRK22J5BBBNN	Rocker switch	$1.38	1	$1.38
--	LED	$0.10	1	$0.10
40-3429-00	Push button	$1.30	1	$1.30
--	Small LED	$0.10	4	$0.40
Labtec 341	Mono headset	$8.69	1	$8.69
7805	5V regulator	$0.71	1	$0.71
LM324	Single supply op-amp	$0.56	2	$1.12
3303C-1-503E	50k trimpot	$0.56	1	$0.56
74LS04	Hex inverter	$0.70	1	$0.70
--	1 MHz crystal	$1.03	1	$1.03
74LS7490	Bi-quinary counter	$0.66	1	$0.66
MV2101	Varactor	$1.01	1	$1.01
TZ03P600E169B00	Variable capacitor	$0.47	1	$0.47
PN2222A	General NPN BJT	$0.14	1	$0.14
74HC4040	High speed 12 stage counter	$0.78	2	$1.56
74LS86	Quad XOR	$0.65	1	$0.65
2N3819	N-JFET	$0.25	1	$0.25
74LS138	Decoder/Demux	$0.89	1	$0.89
--	Various 1/8 W resistors	$0.15	23	$3.45
--	Various capacitors	$0.15	26	$3.90
--	1/2 W resistors	$0.38	2	$0.76
--	Lumped inductor	$0.37	1	$0.37
--	Clip on heat sink	$0.43	1	$0.43
CU-387	Enclosure	$8.52	1	$8.52
PC56	4"x6" copper board	$5.40	1	$5.40
TOTAL			**79**	**$45.16**

Table 1 Parts List Cost (Analysis)

‡ The prices of components/parts are based on those provided by Digikey.

The designed distance of the LPPFMTx is on the order of 1 km (about 3281 feet), according to Amazon.com, the range of prices for a PLL FM transmitter that has a range of 10-30 feet is about $25-60 USD (about $30-70 CAD) and for 150-300 feet, the cost is about $90-160 USD (about $105-185 CAD) [13].

This illustrates the marketability and competitive nature of the LPPFMTx design as a commercial product.

4.2 Equipment and Software

The following lab equipment and commercial software were utilized in the design, testing and debugging of the LPPFMTx.

Lab Equipment

- Breadboard
- Oscilloscope
- Function generator
- DC power supply
- Digital multimeter
- LCR meter
- 12 V lead acid battery

Software

- Microchip Technology Inc FilterLab
- Orcad PSpice
- Electronic Workbench Multisim
- Mathworks Matlab
- Microsoft Excel

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APPENDIX – LPPFMTX BOARD LAYOUT