Design and construction of a 1.045 MHz FM receiver

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Abstract

Karto's general rule: one sent. for each sect. Give numbers (e.g., transmission line speed)

1 Introduction

Modulation of radio frequency (RF) electromagnetic waves is a simple and effective method for long distance information transmission, as exemplified by amplitude/frequency modulated radio. The generation, transmission, and reception of modulated signals are interesting engineering problems which are also accessible to interested amateurs and beginning students of electronics. Simple modulators and demodulators may be built with a minimum of passive and active components (i.e., enough to fit on a small breadboard). RF circuits hold great educational potential for undergraduate students.

Here we present the design and construction of an FM receiver (1.045 MHz with bandwidth 200 kHz). The only non-linear components necessary are a diode and a transistor. The primary purpose of this circuit is for self-edification, but the layout may also serve as a starting point for further exploration of RF circuit design.

The envelope detector as presented is unusable and requires an additional resistor to ground. We additionally present simple improvements and a procedure to characterize receiver noise.

2 FM receiver design

The receiver is comprised of a passive RLC bandpass filter, diode envelope detector, and a common-emitter amplifier chained between antenna input and speaker output. Blocking capacitors between different functional sections enable voltage biasing.

2.1 Bandpass RLC filter

The input signal is first passed through an RLC filter centered at approximately $1.045 MHz$ with the -3 dB point at ± 200 kHz on each side. For component values R, L, C (resistor, inductor, capacitor) and input signal component with angular frequency ω, the gain of this filter is given by the equation:

$$\left| \frac{V_{\text{out}}}{V_{\text{in}}} \right| = \left[1 + (RC)^2 \left(\frac{\omega_0^2 - \omega^2}{\omega} \right)^2 \right]^{-1/2}$$

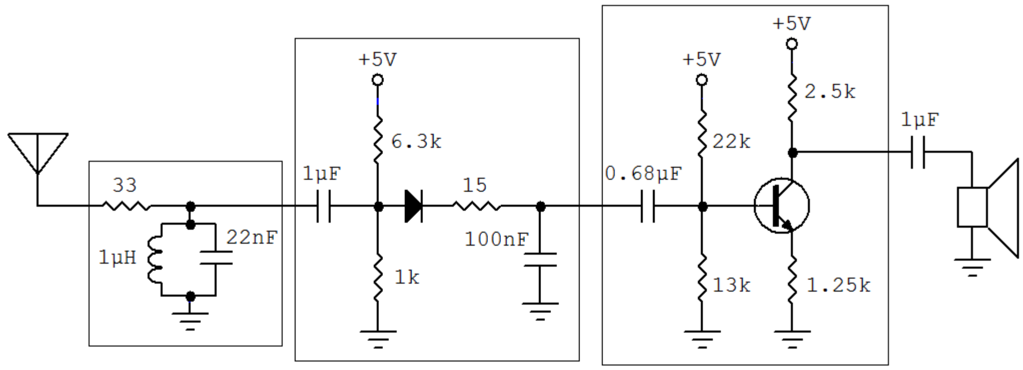

Figure 1. FM receiver circuit diagram with component values.
Boxes demarcate functional components (see corresponding sections in text).

Here $\omega_0 \equiv 1/\sqrt{LC}$, emphasizing that this filter has unity gain at $\omega = \omega_0$. The -3 dB roll-off frequency occurs when the gain is equal to $1/\sqrt{2}$, or when:

$$(RC)\frac{\omega_0^2 - \omega^2}{\omega} = 1$$

Let the bandwidth be denoted by Δf, with corresponding cut-offs at $f = f_0 \pm \Delta f/2$, where $f_0 = w_0/(2\pi)$. This gives:

$$2\pi f_0 RC \approx \frac{f_0}{\Delta f}$$

as a prescription for our cut-off. Our component values $R = 33\ \Omega, L = 1\ \mu\text{H}, C = 22$ nF give $f_0 = 1.073$ MHz with bandwidth $\Delta f = 220$ kHz. Figure 2 plots the frequency-dependent gain along with the transmission band of interest at 1.045 MHz.

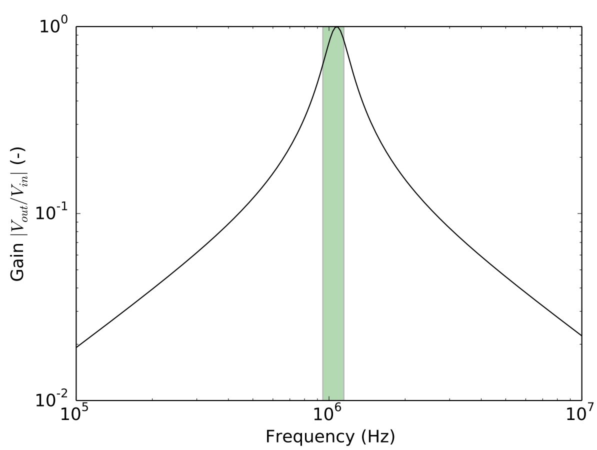

Figure 2. RLC filter gain against input frequency f (Hz).
FM signal bandwidth plotted in light green.

2.2 Diode envelope detector

We use a diode in series with a low-pass RC filter as a rudimentary envelope detector. Prior to a diode, we use a blocking capacitor and voltage divider to apply a bias voltage of 0.68 V to the input signal; this allows the positive half of the signal to be passed mostly unattenuated by the diode.

The blocking capacitor value is set by the behavior of the capacitor and the biasing voltage divider as a high pass filter. Looking into the voltage divider, the resistors are seen in parallel and so the input impedance is about 860 Ω. To allow our carrier signal ($\sim$ 1 MHz) to pass, the blocking capacitance must be at least 0.2 nF, which is satisfied by our 1 μF capacitor.

Our diode circuit is expected to obtain a signal envelope as follows. The diode extracts only the positive half of an input signal, with the diode's knee voltage compensated for by our voltage biasing. However, when the carrier signal peaks and begins to decrease, the RC circuit prevents the maximum imposed voltage from decaying immediately; it is forced to decrease over a timescale RC. The voltage is only "unpinned" once the next carrier cycle passes through the diode.

The diode is placed in series with a low-pass RC filter of cutoff frequency $\sim$ 110 kHz. In actuality, the cutoff frequency should have been closer to 1 MHz for envelope detection. Our envelope detector did not operate correctly anyways, which we discuss further below. We plot the gain of the low-pass filter in Figure 3, to show that audible frequencies will not be attenuated in a correctly designed circuit.

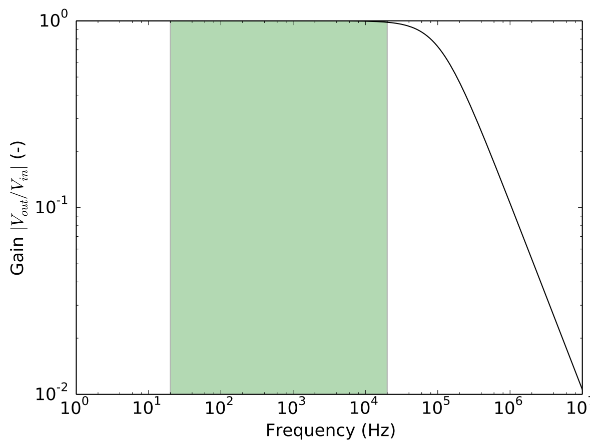

Figure 3. Low-pass RC filter gain as a function of input frequency f (Hz). Approximate human hearing range plotted in light green.

2.3 Common-emitter amplifier design

We pass the extracted envelope curve from the diode demodulator to a common-emitter transistor amplifier. Our choice of component values and following explanation of circuit operation are guided in large part by *Horowitz and Hill* [1989].

The transistor's quiescent base voltage is set by a biasing voltage divider, which controls emitter voltage. For appropriate choice of collector and emitter resistors, the collector voltage amplifies the base voltage signal. The gain is given as $-R_c/R_e$ (where R_c, R_e denote collector and emitter resistors respectively).

For maximal voltage swing, the quiescent collector voltage should be 2.5 V (or, $V_{cc}/2$). We choose a quiescent current of 1 mA and hence set collector resistor to 2.5 kΩ. We set the emitter resistor at 1.25 kΩ for a gain of 2. The quiescent emitter voltage is then 1.25 V, and the quiescent base voltage should be ~ 1.85 V. We bias the base voltage using 22 kΩ and 13 kΩ resistors.

In actual practice, we used slightly different values ($R_E = 1.5$ kΩ, $R_C = 2.7$ kΩ, voltage divider resistors 22 kΩ and 12 kΩ). However, our results are not significantly affected.

The blocking capacitor prior to the amplifier biasing circuit acts as a high-pass filter. The input impedance, looking into the transistor base, is ~ 8 kΩ (set primarily by the two divider resistors in parallel). We choose 0.68 μF as our capacitor, which gives a cut-off frequency of 30 Hz, at the lower end of the audible range (cf. Figure 3).

2.4 Receiver impedances

External loads or sources (antennae, transmission lines, speakers) connected to our receiver should be impedance matched to maximize power throughput.

The output impedance of the amplifier sets the receiver's output impedance, as the amplifier transistor buffers any lower impedance upstream. In our circuit, the output impedance is the parallel impedance of the transistor and collector resistor, or roughly 2.5 kΩ. This is much larger than the 50 Ω impedance of transmission lines, or the 8 Ω impedance of our speaker.

An emitter-follower circuit may be placed after the amplifier, then, to decrease the receiver's output impedance by a factor of $\sim 1/\beta$; β is the transistor amplification factor. We may make further adjustments by placing resistors in parallel with the follower output, or adding resistors in series with the speaker at the end of the line (although, I'm not sure what is common practice).

3 Results

3.1 Receiver behavior

To test the RLC bandpass filter, we input a sine wave of varying frequencies and measured the output across the LC tank circuit. We obtained a maximum gain of 0.83 at input frequency 1.05 MHz (caveat: we may have used incorrect termination procedure for this measurement, but this only impacts our gain measurement). The circuit qualitatively showed the correct roll-off behavior.

When we input an FM signal at 1.045 MHz and observed the filter output on an oscilloscope, the signal was correctly converted into an AM signal with envelope code matching output audio. We also confirmed that the voltage divider added a correct bias of approximately 0.7 V.

* Explain our odd troubles with the diode detector. Whether the circuit helped was very equivocal...

A brief search suggested that a more effective envelope detector might be generated by placing the resistor and capacitor in parallel.

* Discuss frequency / clipping issues here? (for amplifier)

3.2 Noise characterization

We attempted to characterize the Johnson-Nyquist noise in a resistor.

Blah blah blha amplifiers blah blah blah bandwidth blah blah blah oscilloscope noise.

* Noise measurement

4 Discussion

4.1 Envelope detector design

4.2 Common-emitter amplifier design

The common-emitter amplifier gain may be improved by adding an emitter capacitor (C_E) in parallel with the resistor capacitor. The new gain is:

$$\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right| = \left[\left(\frac{R_C}{R_E}\right)^2 + \omega^2 R_C^2 C_E^2\right]^{1/2}$$

By choosing $C_E = 50$ nF, we were able to observe 10x gain at input frequency 10 kHz. However, the gain with capacitor preferentially amplifies higher frequencies.

* Amplifier test - explain Allan variance test, but give reasonable physical numbers

5 Conclusion

What you're gonna do with this next. Don't rewrite your intro/abstract.

Use plain english. Don't worry about being technical, or too concise...

We are missing a substantial number of error estimates (usually numbers are good to the last digit, maybe $\pm 2 or 4$ in that least significant digit). And, we did not take many measurements to gauge our circuits' frequency responses in actual operation.

6 Acknowledgments

Thanks to Patrick and Kyle for much patience and lots of time spent working in lab. Much thanks to Baylee, Karto, and Prof. Parsons for answering our questions and helping us root out some mistakes (though not all, as evidenced here). Other lab members are thanked for discussions of variable seriousness and positive utility.

7 References

Horowitz, P. and W. Hill (1989), *The Art of Electronics*, Cambridge Univ. Press, Cambridge, UK.