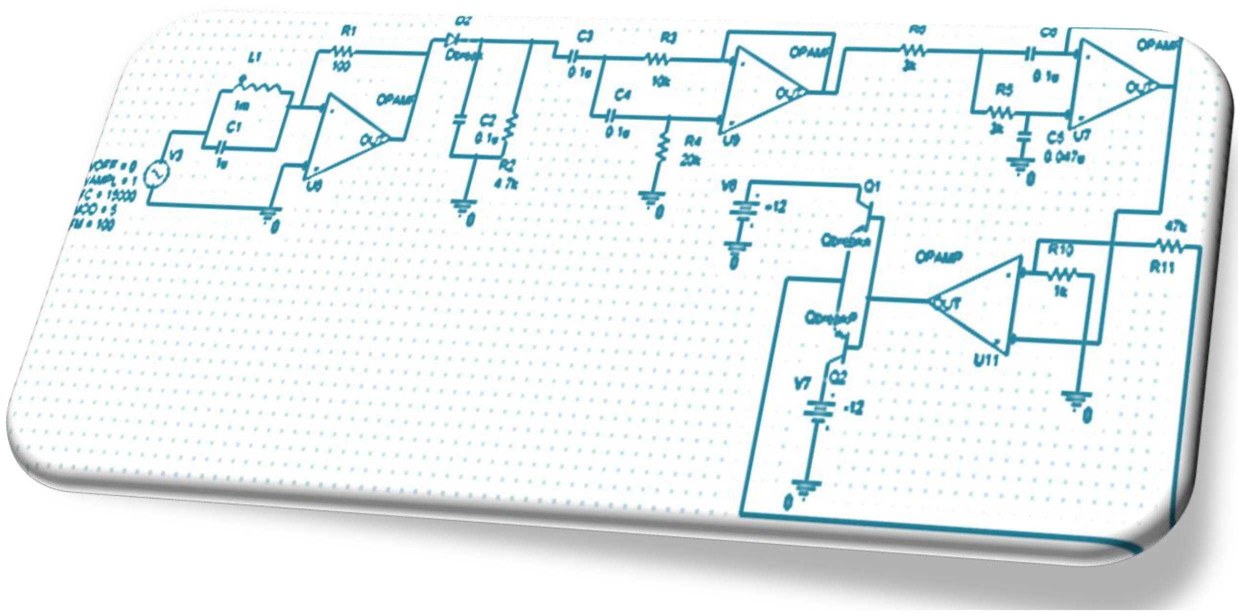
Washington State University

School of Electrical Engineering and Computer Science

EE 352 Design Project
FALL 2015 -FM Receiver



Alexis Mekueko
Chemical Engineering and Power Track
Mohamed Alzahmi
Electrical Engineering/System Track
Biniyam Obsu
Electrical Engineering/General Track

12/18/2015

FM Receiver

Final Design Report

Abstract

The FM receiver has been designed, simulated and built to carry out circuits capable of demodulating and playing a single tone FM-modulated signal generated by the signal generator and delivered to the circuits via BNC cable. The following specifications were determined: modulation index(8), amplitude(1V), 12V DC source, carrier frequency(15 kHz) and operating at 100 Hz and 1000 Hz. The FM receiver was successfully simulated in ORCAD SPICE and experimentally tested through a step-by-step process which inludes: the differentiator, the envelope detector, the bandpass filter, the power amplifier and the speaker. The final output was an acute sound from AC-1005G-RPA-LF and a nice 12Vpeak to peak sine wave from the oscilloscope.

Alexis Mekueko

12/18/2015

Introduction

The FM receiver is based on the idea that a generated message can be carried out through regulated system and delivered to a speaker. To achieve such a communication system, three steps are required: design, simulation and the experimentation. For the design, we need to recall some knowledge in order to understand the conception of the project[1]. According to Lawrence [2], “Frequency modulation is a form of analog angle modulation in which the baseband information carrying signal, typically called the message or information signal m(t), varies the frequency of a carrier wave.” From this definition, it is clear that the design will require circuits that can handle “signal” from the input, transit to regulated system and output to a speaker. According to the requirements, a single tone FM-modulated signal(Eq.2) generated by the signal generator, which carries the message signal. In order to obtain the message signal, we will need to differentiate this signal and use the envelope detector to pick up the message signal. However such a signal still distorted and requires a filter such as bandpass to sweep between 100 and 1000 Hz, and finally amplifies to meet the specification of the speaker (AC-1005G-RPA-LF)[3].

Thus, the design will involve: the frequency discriminator, the envelope detector the bandpass filter and the power amplifier. We will use the ORCARD SPICE to simulate each block of the FM receiver as shown in Fig.1.Finally, we will build up and test in the circuit laboratory these circuits: bandpass differentiator, the envelope detector, the bandpass filter.

$$m(t) = A_m \cos(2\pi f_m t) \quad \textbf{Eq.1}$$

Message signal

A_m = the amplitude of m(t).

f_m =the frequency of m(t).

$$g_{FM}(t) = A_c \cos\left(2\pi f_c t + 2\pi k_f \int_0^t m(x)dx\right)$$

FM Signal, Eq. 2

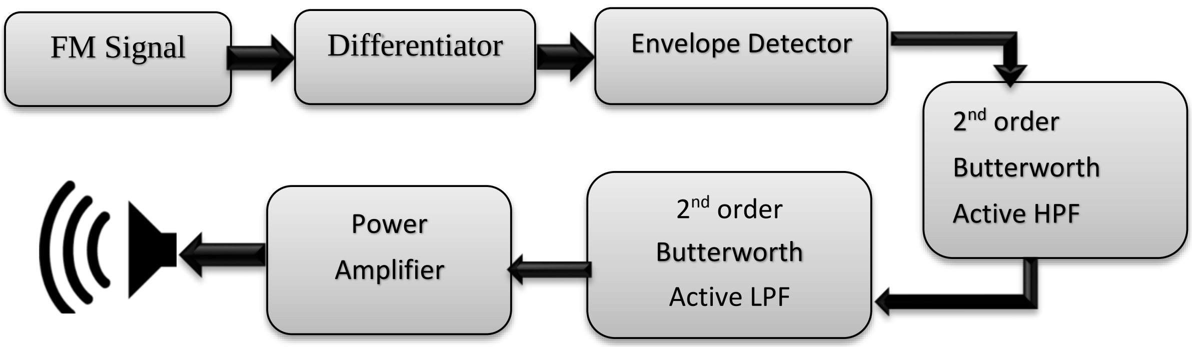


Fig.1 FM Receiver Building Block Diagram

Theory

Frequency Discriminator

How does the message signal will be carried out to the speaker? The answer to this question starts with the designing of the frequency discriminator. From the signal generator source, a single tone FM-modulated signal is generated. This input signal which carries the message signal is not clean. So, the first step is to demodulate the FM signal (Eq.3) by using the differentiator to convert the FM signal into an amplitude signal(AM signal), appendix A. Using Eq.5 which derives from Eq.4, we defined β, the modulation index (Eq.6), Δf, the frequency deviation, B_T, bandwidth of the message signal (Eq.7). f_c, the carrier frequency that must be between 10000 and 15000 Hz and f_m, the frequency of the message signal(100Hz, 1000Hz).

$$g_{FM}(t) = A_c \cos\left(2\pi f_c t + \frac{k_f A_m}{f_m}\sin(2\pi f_m t)\right) \qquad \text{Eq.3}$$

$$\frac{d}{dt}[g_{FM}(t)] = A_c \sin\left(2\pi f_c t + 2\pi k_f \int_0^t m(x)dx\right)\frac{d}{dt}\left(2\pi f_c t + 2\pi k_f \int_0^t m(x)dx\right) \qquad \text{Eq.4}$$

$$\frac{d}{dt}[g_{FM}(t)] = A_c(2\pi f_c + 2\pi k_f m(t)) \sin\left(2\pi f_c t + 2\pi k_f \int_0^t m(x)dx\right) \qquad \text{Eq.5}$$

$$\beta = \frac{k_f A_m}{f_m} = \frac{\Delta f}{f_m} \quad \text{Eq.6} \qquad B_T = 2[\Delta f + f_m] \quad \text{Eq.7} \qquad H(j\omega) = -jR_f C\frac{\left(\omega^2 - \frac{1}{LC}\right)}{\omega} \quad \text{Eq.8}$$

Simulation

From the above equations, we designed the differentiatorr as shown in fig.2 and 3: VSFFM source (Voff = 0V, amplitude =0.5, 1V, 1 kHz<f_c<15 kHz, modulation index, f_m =100, 1 kHz) the values of the inductor in parallel with the capacitor and the resistor were found from the transfer function (Eq.8): the cutoff frequency (w_o), $w_o = \frac{1}{\sqrt{LC}} = w_c + \delta$, with $\delta > 2\pi\Delta f = 2\pi A_m k_f$, where $A_m k_f$ were chosen by the signal generator. $w_o = 10^5$ rad/s, L = 1mH,C = 0.1µF, R = 470 Ω, β = 8.

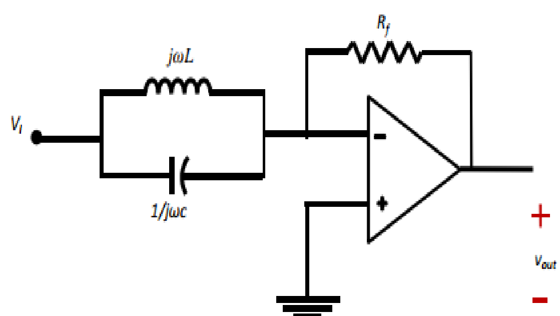


Fig. 2 Frequency Discriminator

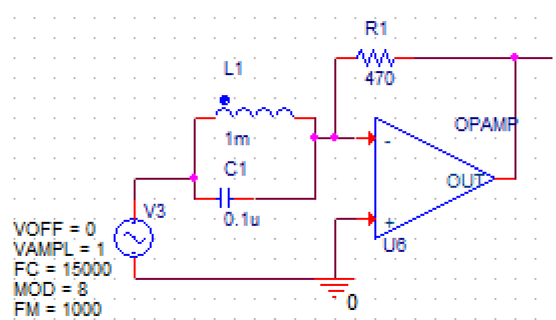
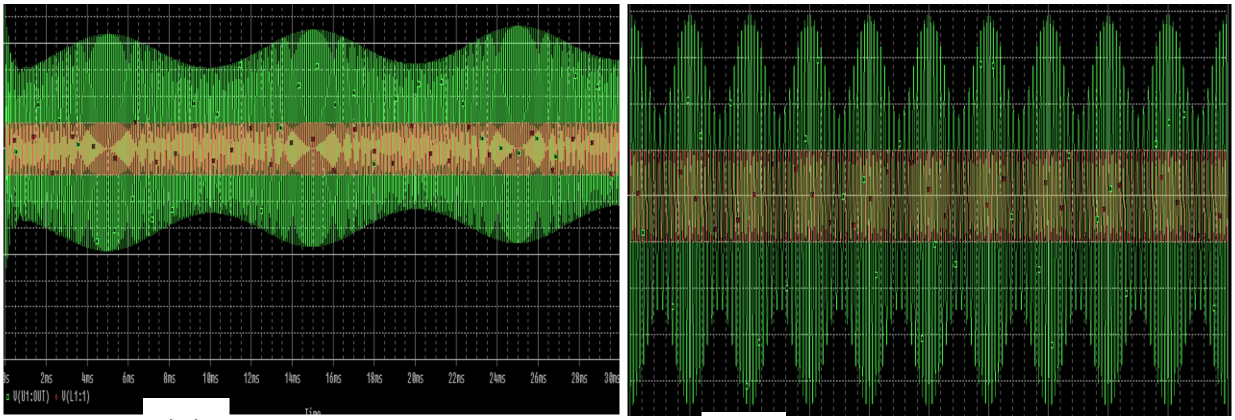


Fig.3 Differentiator schematic



(a) (b)

Fig.4 Differentiator output waveform (a), f_m=100Hz and (b), f_m=1 kHz in PSPICE.

After running a transient response (time, 30ms aand maximum step size, 1µs), we obtained Fig.4 (a) at 100Hz and 1kHz. The red signal represents the sinusoidal wave of the FM input signal with the amplitude of 1Vand the green wave shows the output from the differentiator.

Envelope Detector

The AM signal output by the differentiator carried the message signal which is the envelope of the Fig4. So, we designed the envelope detector to pick up this envelope. Since the envelope on top and base were the same, there was no need to pick up the top and base. Thus, the envelope detector(Fig.5 and 6) was designed to pick the top envelope.The diode was used to filter out the negative half-cycle from the AM signal, leaving the positive half-cycle. The capacitor was charging as the voltage of the positive half-cycle increases, and discharging through the resistor as the voltage decreases in the half-cycle. The following equations 9 and 10 were used to determine the elements of the envelope detector. After calculation, capacitor 0.1µ F, and R = 4.7kΩ.

$$g_{FM}(t) = A_C \cos(w_c t) + A_C K_a m(t) \cos(w_c t)$$ Eq.9

$$Envelope\ of\ g_{FM}(t) = A_c(1 + \beta \cos(w_m t))$$ Eq. 10

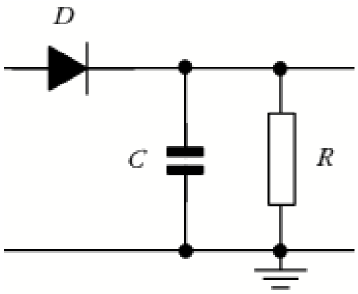


Fig. 5 Envelope Detector

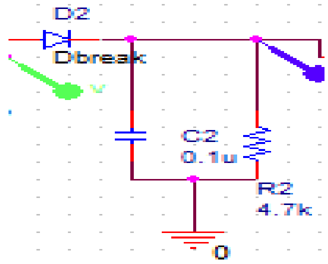


Fig. 6 Envelope Detector schematic

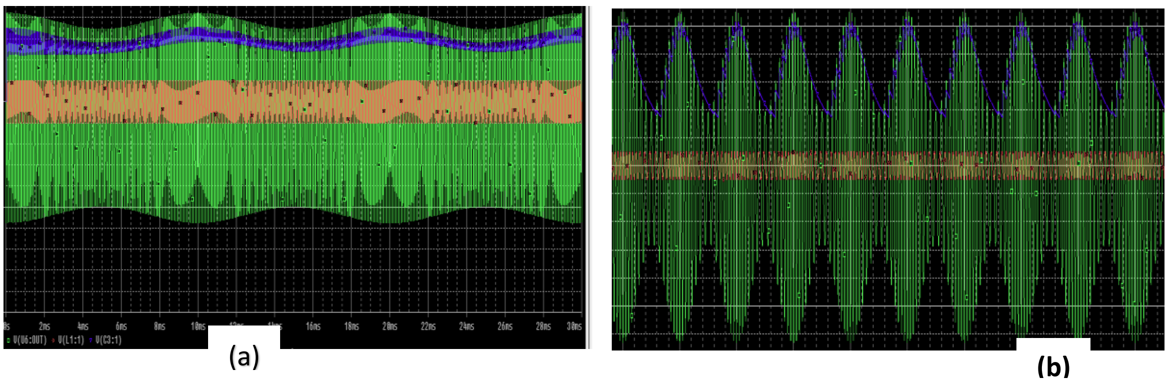


Fig.7 Envelope Detector output waveform (a), f_m=100Hz and (b), f_m=1 kHz in PSPICE.

Keeping the same specifications as previously used for the differentiator, Fig.7 was displayed from the PSPICE showing the blue waveform copied of the message signal.

Band Pass Filter

The simulation of the envelope detectors showed the top envelope of the AM signal being copied, however, this message signal needed to be filtered out; thus, we designed a bandpass filter to eliminate the DC offset and filter out the message signal in the bandwidth(100Hz-1kHz). we used a highpass filter(HPF)[4] as shown in Fig.8,9 in series with a lowpass filter(LPF) [4], Fig.10, 11 to act as a band pass filter. Both filters are Butterworth 2nd order filters[5]. These filters were chosen because the frequency response is flat with no ripples in the passband nor stopband[6]. In order to make them Butterworth filter the values for the components need to be chosen carefully. The equations below show how the values were calculated.

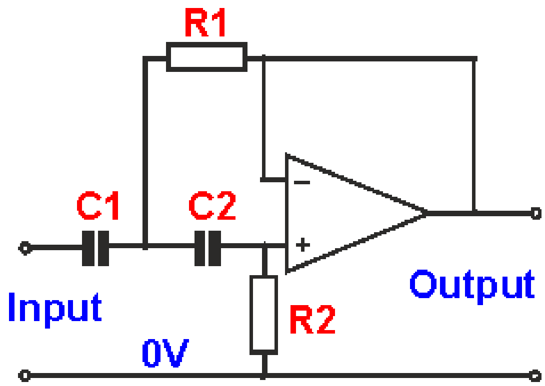
$$H(s)_{HPF} = \frac{S^2}{S_2 + 2\zeta w_m S + w_m^2} \qquad H(s)_{HPF} = \frac{S^2}{S_2 + \frac{2}{R_2 C} S + \frac{1}{R_1 R_2 C^2}}$$

Eq.11

$$\boldsymbol{H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}} \qquad H(s)_{LPF} = \frac{{}^{1}/_{R^2 C_1 C_2}}{S_2 + \frac{2}{RC_1} S + \frac{1}{C_1 C_2 R^2}}$$

Eq.12

It is important to note that the two filters Butterworth $\boldsymbol{\zeta}$ needs to equal 0.7071(Eq.11,12). According to the requirements of the project, we needed to handle the message signal at 100Hz and 1000 Hz. Thus, we chose w_m to equal 100 Hz for the HPF(Eq.11) so that all frequencies below 100 Hz were filtered out. W_m for the LPF(Eq.12) was chosen to equal 1kHz, making it so that all frequencies above 1kHz were filtered out. This made a band pass filter with a bandwidth (100Hz-1kHz).



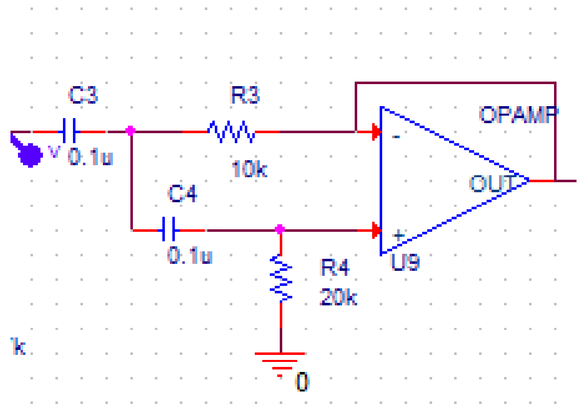
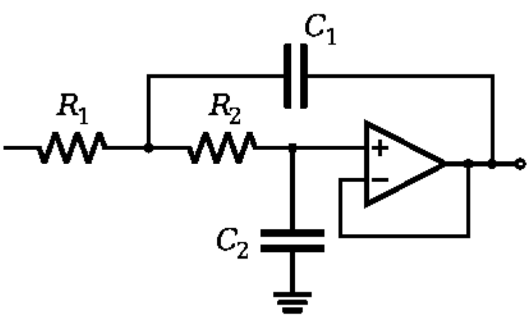


Fig.8 2^{nd} Order HPF Butterworth Filter.   Fig.9 2^{nd} Order HPF Schematic .

For the HPF we determined the capacitors, C1 = C2 =0.1µF, the resistors, R_1 = 10kΩ

R_2 = 20kΩ



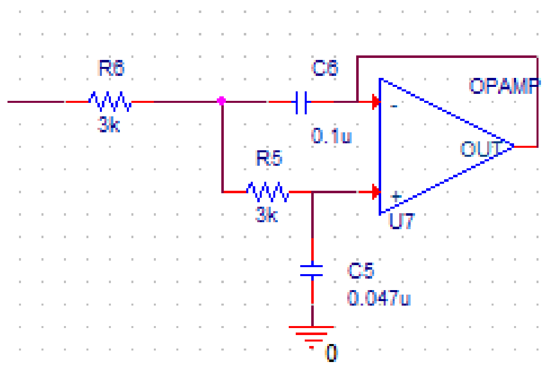


Fig.10 2^{nd} Order LPF Butterworth Filter.   Fig.11 2^{nd} Order LPF Schematic .

For the LPF we choose C_1 to equal 0.1µ F, and using (13) with (14) we solved for both C_2 and R.

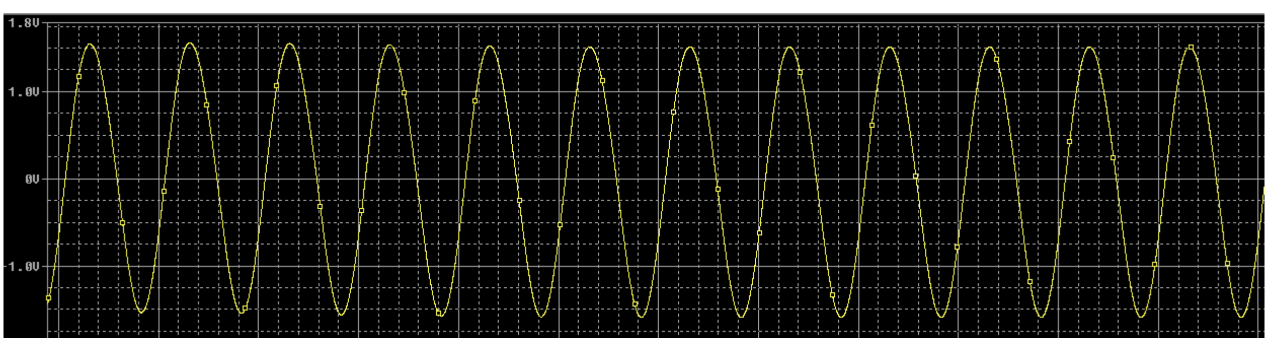


Fig.12 Bandpass output waveform f_m=1 kHz in PSPICE

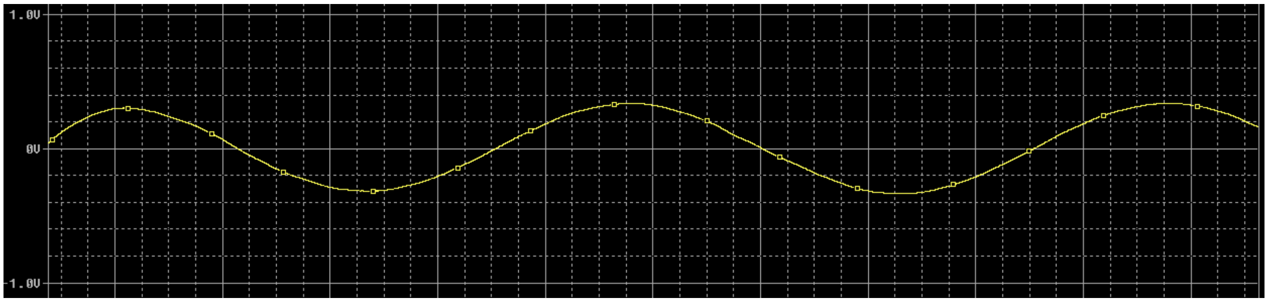


Fig.13 Bandpass output waveform f_m=100 Hz in PSPICE

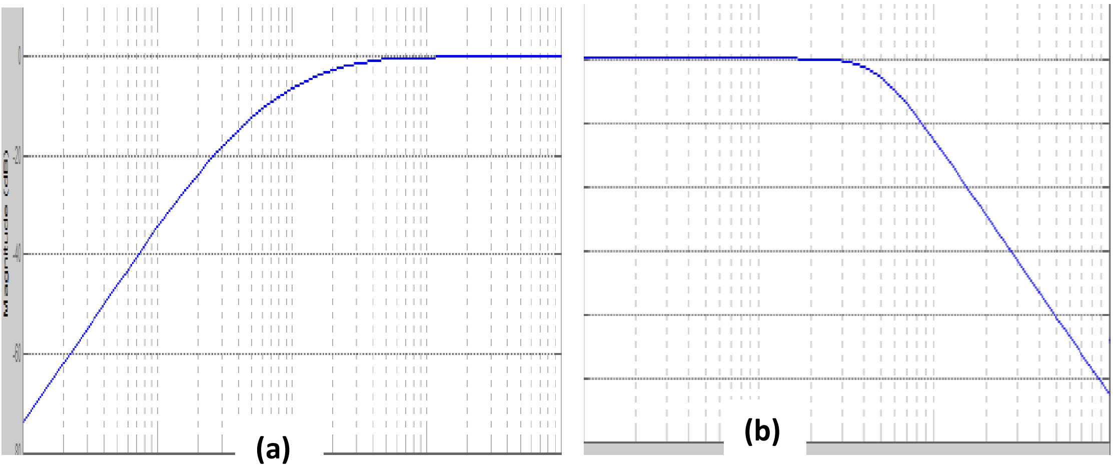


Fig.14 HPF (a), f_m=100Hz and LPF (b), f_m=1 kHz Bode plot in Matlab

Again, keeping the same specifications as previously used for the differentiator and the envelope detector, Fig.12 and 13 were displayed from the PSPICE showing the yellow sine waveform which is the message signal at 100Hz and 1kHz. The two sine waves look nice, however, the amplitudes are less than 2V. Fig.14 shows the bode plots obtained after running the transfer function in matlab:Fig.14(a) is the frequency response of the highpass filter at 100Hz cutoff frequency and the Fig.149(b) is the frequency response of the lowpass filter at 1kHz cutoff frequency. All the details, codes phase response are shown in appendix B.

Power Amplifier

Having the bandpass filtered output the desired message signal m(t), we looked at the amplitude of the sine wave which appear to be very small compared to the minimum voltage required to speaker[3]. Thus, the need to amplify the output signal by the bandpass. The amplitude of the sine wave was less than two volts for both low and high frequency. In order to get the speaker deliver the message signal (sound), we needed to design the power amplifier(Fig.15)[8] to level up the amplitude to the acceptable operating range(3V to 8V) of the speaker. Based on the project reading assignment, we chose the class B power amplifier associated with op27[7] to obtain:

$R_f = 47k\Omega$, $R_g = 1k\Omega$, $R_L = 1k\Omega$ and two transistors Q_1 (npn), Q_2(pnp).

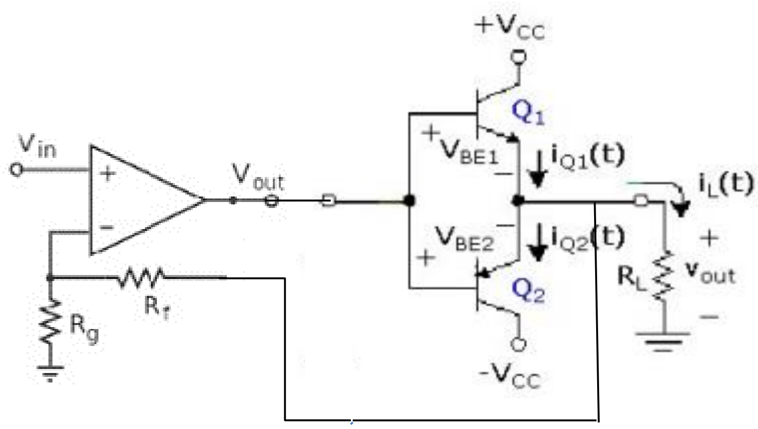


Fig.15 Modified Class B Power Amplifier.

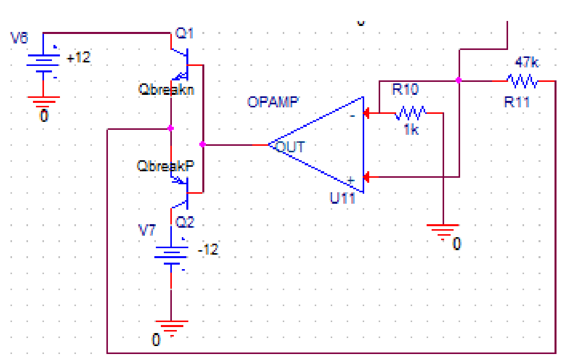


Fig.16 Modified Class B Power Amplifier schematic.

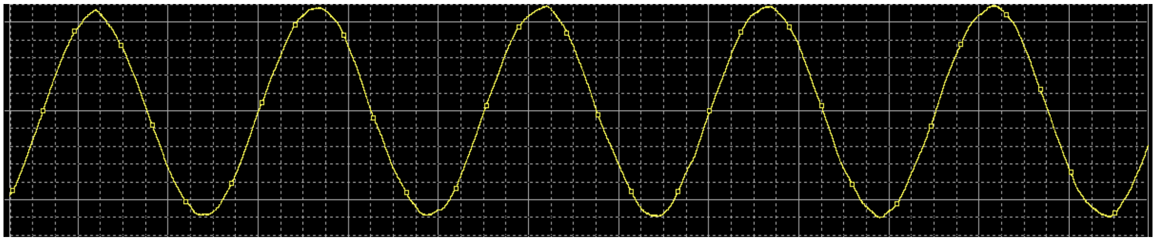


Fig.17 Class B Power Amplifier sine Wave output

Fig.17 shows the yellow sine waveform which is the final message signal delivered to the speaker.

Note: the increase in the amplitude (6V) of the message signal.

Methodology

The overall designed, simulated and tested step-by-step. The overall FM Receiver was an assembly of 5 blocks. Each block was built separately, however, relying on successive dependency. From the PSPICE simulation, we needed to gather:

Student parts kit[9], the laboratory devices(fig.19), four op27(Fig.18), one 1N3064 (small signal diode)[10], one TIP31CFS (NPN transistor) [11], one TIP32CFS(PNP transistor)[12], one AC-1005G-RPA-LF(speaker), we used P3 in Fig.19 to measured all the resistors and P1 in fig.19 for capacitors. These passive elements were calculated with ±5% tolerance, only inductor (1mH) were used, breadboards, wires probes and BNC cable(signal generator).

The op27 used in this project is described as follow:

- Applied +12V DC to the positive supply voltage node (V+) that is pin 7.
- Applied -12V DC to the negative supply voltage node (-V) that is pin 4.
- Output pin that is pin 6.
- Noninverting input (+) that is pin 3.
- Inverting input (-) that is pin 2.

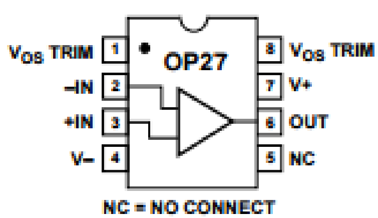


Fig.18 Operational Amplifier Pin Configuration

Agilent Technologies E4980A (P1)

Tektronix TDS2014B Digital Storage Oscilloscope (P2)

Fluke 45 Dual Display Multimeter (P3)

GW INSTEK AFG-2012 Signal generator (P4)

Fig. 19 Laboratory devices

Block 1: Frequency Response

For the first block , we set the 1mH in parallel with 0.1µF in series to 470 Ω resistor connected to pin 2 of the op27 and pin3 grounded. Then the probe was placed on pin 6 to display the output on p2, Fig.22.

Block 2:Envelope Detector

We set pin 6 used in block 1 to 1N3064 in series with 0.1µF in parallel with the 4.7k Ω.

Note: the capacitor and resistor were grounded before placing the probe to measured the output on fig.23.

Block 3: Highpass Filter

Having measured the output by the envelope detector, we connected the 4.7kΩ used in block 2 in series with 0.1µF in parallel with 0.1µF which is in seris with 20k Ω(grounded) and connected to pin 3 of op27, then added a 10kΩ between the two identical capacitorsand connected to pin 2 as negative feedback and place the probe at pin 6 to measured the output on Fig.24(a).

Block 4: Lowpass Filter

After making sure the HPF was filtered out the message signal at 100Hz, we need to build up a LPF to get the 1kHz. Now, we connected the pin 6 used in block 3 in series with 3kΩ in parallel with 3kΩ which is in seris with 0.047µF(grounded) and connected to pin 3 of op27, then added a 0.1µF between the two identical capacitors and connected to pin 2 as negative feedback and place the probe at pin 6 to output the message signal(fig.24).

Block 5: Power Amplifier

The power amplifier was needed to level up the low amplitude output by the bandpass. Thus, we built up a voltage divider (47kΩ/1k kΩ) as negative feedback to op27 and connected pin 6 to the base (B) of the TIP31CFS in series with TIP32CFS. Then, applied +12V DC source to the NPN collector (C) and -12V DC source to the PNP emitter(E). Finally, the 47 kΩ was connect to the node (NPN (E) and PNP(C) and connected the speaker. Figure 20 is the overall design and figure 21 represents the 5 blocks including the speaker.

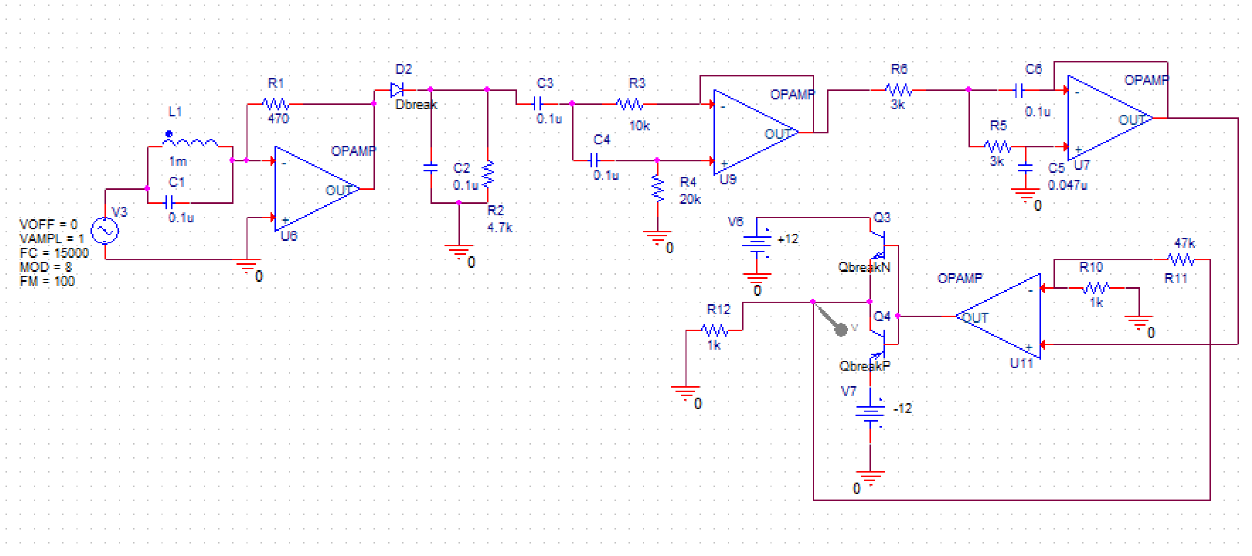


Fig. 20 – Overall FM Receiver Schematic

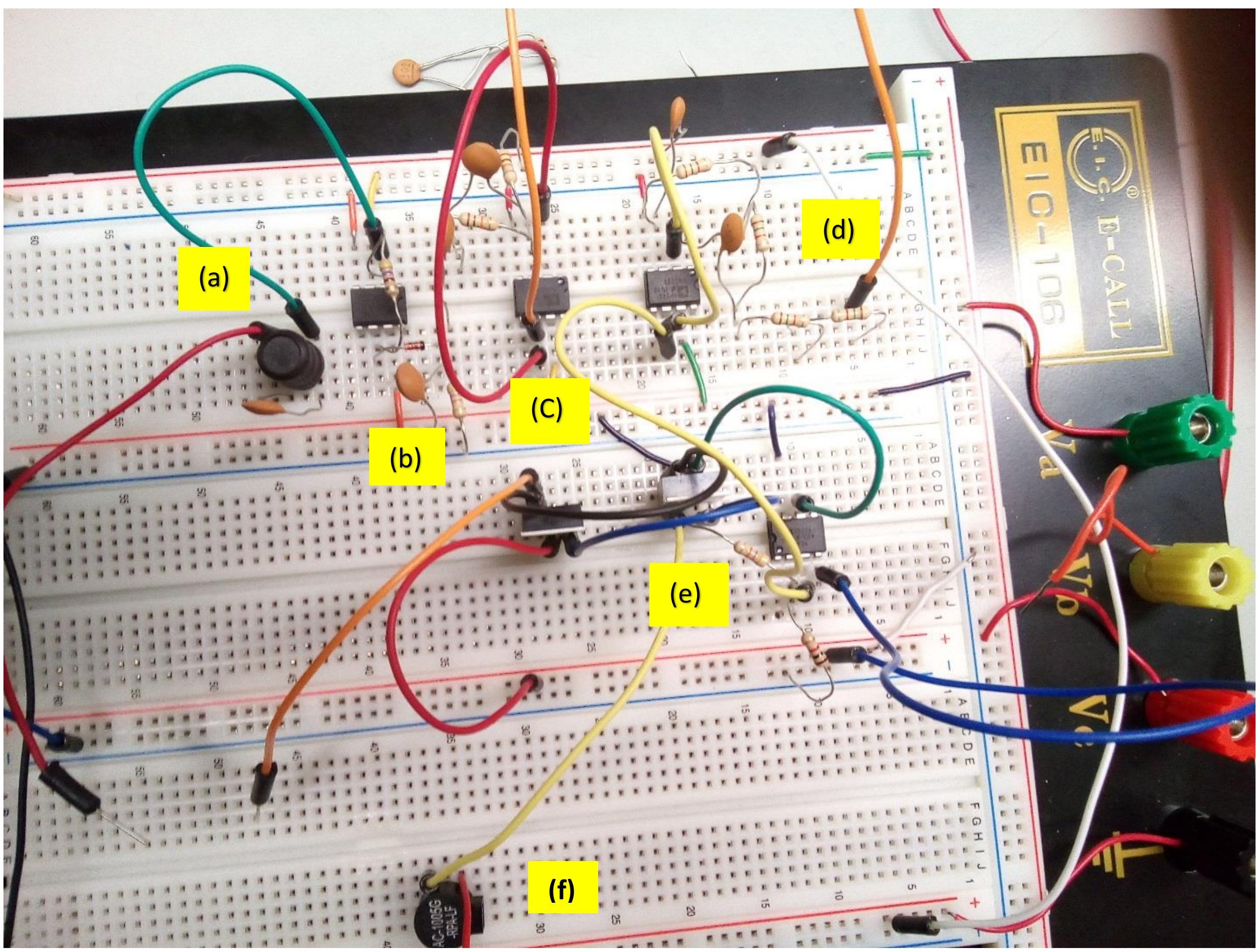


Fig.21 – Overall FM Receiver built up.

Results and Analysis

From Figure 21:

a-Differentiator , b-Envelope Detector, c-High Pass Filter,

d-Low Pass Filter, e-Power Amplifier

f-speaker.

Output from P2

Frequency discriminator

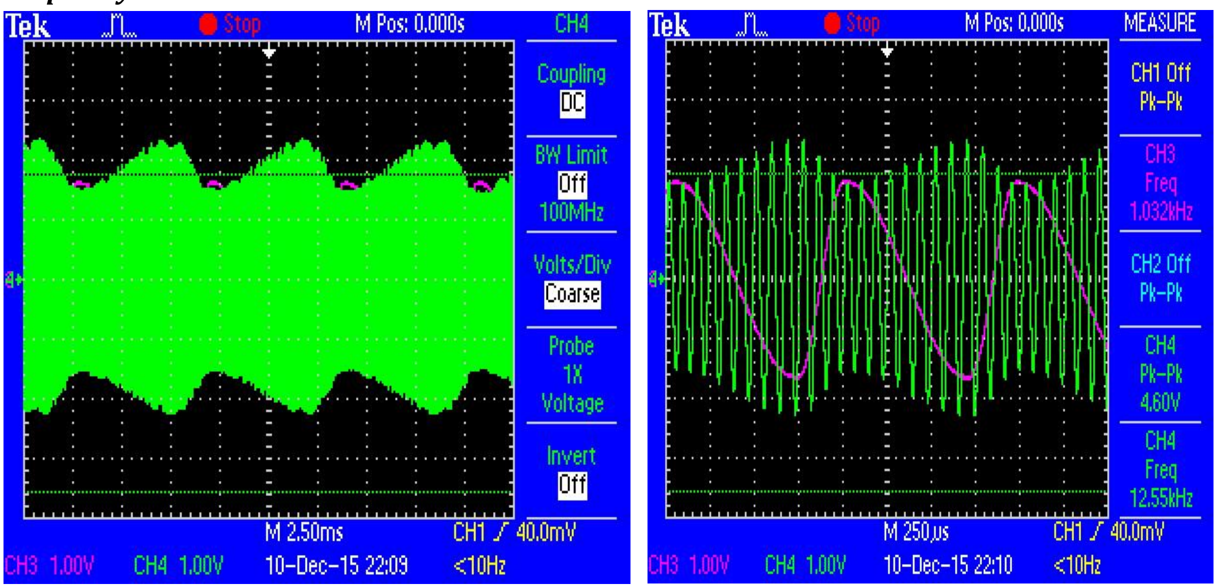


Fig.22 Differentiator output at (a)100Hz (b) 1000Hz

Figure 22 shows the output the from the differentiator at (a) 100Hz and (b) 1kHz. These two output both carry the message signal which agree with the matlab analysis(appendix B). One concern in the differentiator is to make sure the slope does not drop to fast so that at least 0.7V is there to turn on the diode.

Envelope Detector

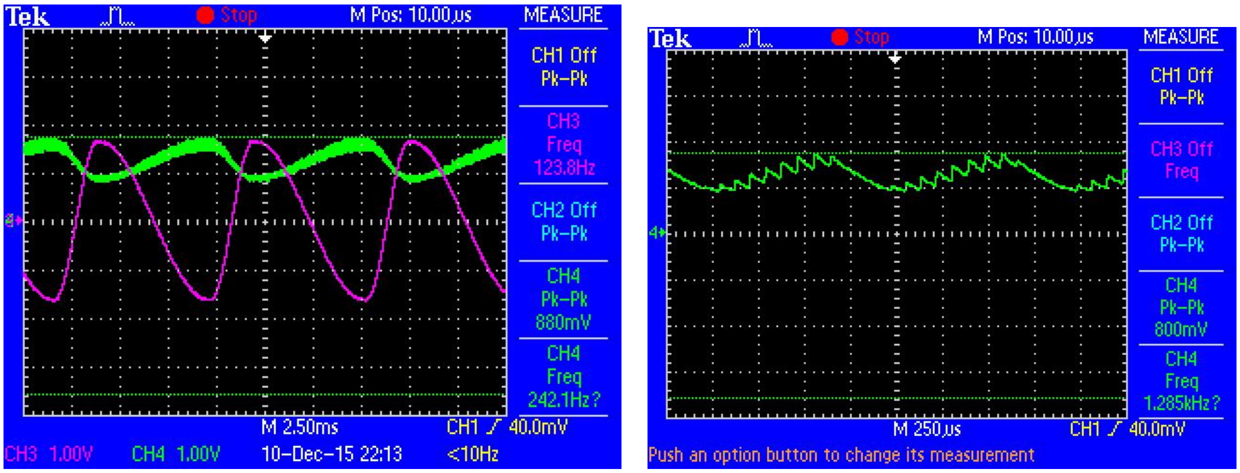


Fig. 23 Envelope Detector output at (a) 100Hz (b) 1000Hz

Figure 23 shows the message signal (green wave form) which is the envelope from the differentiator. We can conclude that the differentiator met the 0.7 V required to turned on the diode.

Bandpass Filter

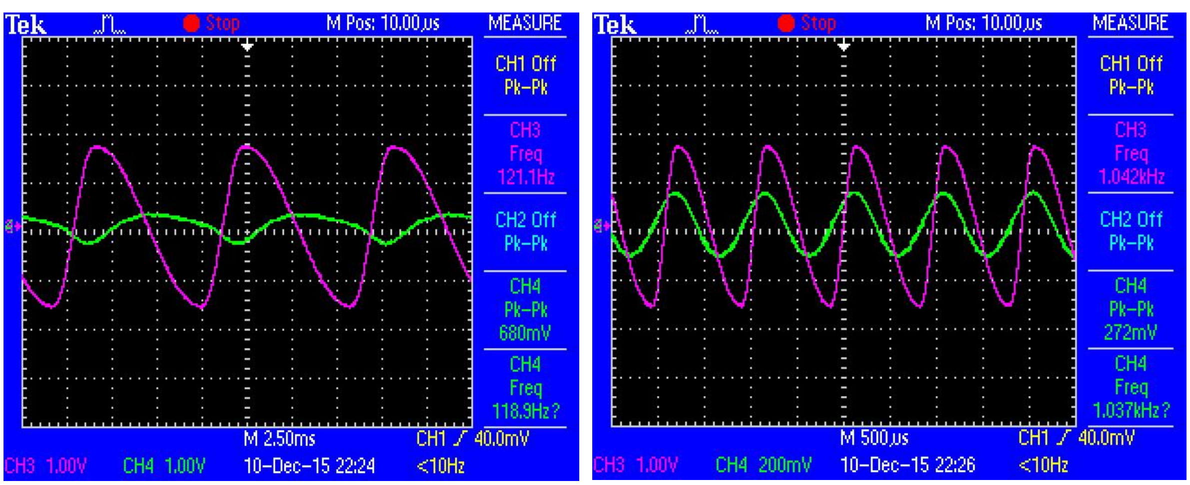


Fig.24 Bandpass Filter output at (a) 100Hz (b) 1000Hz

Figure 24 shows the bandpass filtering out the message signal (green sine wave) at very low amplitude. There is a huge gap bettwen the two amplitude and the reason is due to the fact that the magnitude of the output from the differentiator is not pateau as shown in Appendix B, matlab of the transfer function equation(8). These difference are likely to impact on the final message signal (sound) by the speaker.

Power Amplifier/Overall output

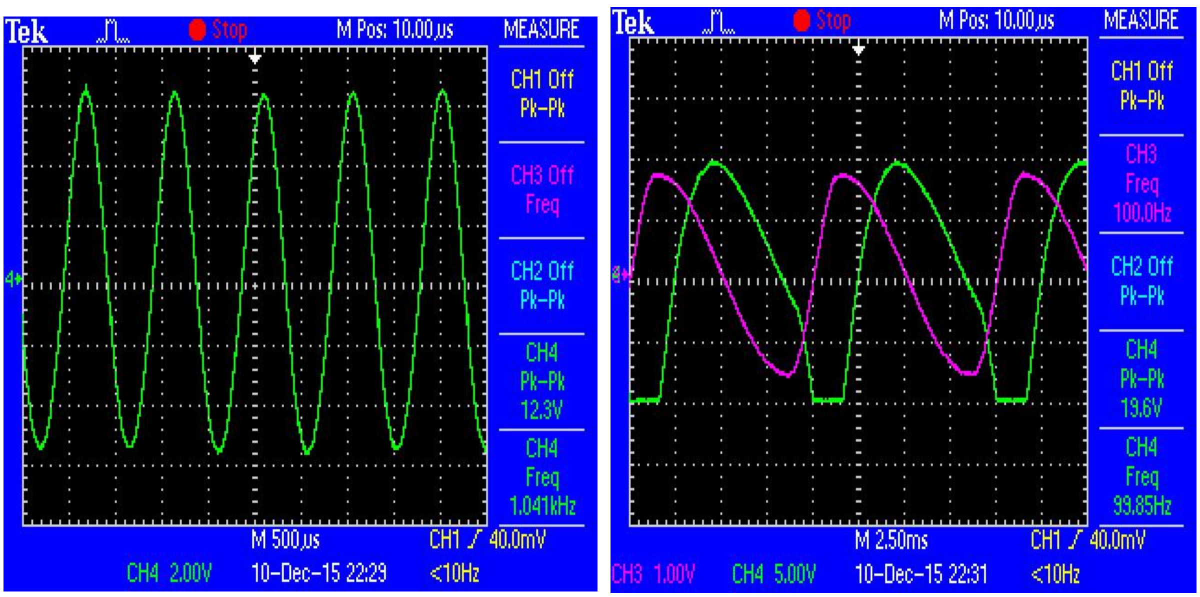


Fig. 25 Power Amplifier output at (a) 100Hz (b) 1000Hz

Figure 25 is the last block that ultimately delivered the message signal to the speaker. As we can seen in figure 24, the bandpass filtered out the message signal but the amplitudes are so low that the speaker will not play the sound. In order to meet the speaker specification, we need to increase the gain on the signal from the bandpass filter. Therefore, we dsigned the power amplifier with a voltage divider negative feedback to level up the gain. Finally, the gain displays in figure 25 is ≈6V amplitude (acceptable) and a nice sound delivered by the speaker.

There was a successive dependency in the overall building block, meaning each indidual block depends on the output from the precedent block.

The difficulty of this project was to determine the passive and active elements that can be easily pick up from the student part kit.

The overall design of the FM receiver was built up of six blocks that all play an intricate role in successively outputting the message signal through the speaker. Every block has different circuit setups that takes different theoretical calculations and different methods of troubleshooting the problems. In the simulation process, when designing the circuit, we took the approach of going one stage at a time so that we could easily figure out the mistakes that were made either by calculations or configuration errors. In the implementation of the FM Receiver circuit, we chose to use a large breadboard setup so that we had enough space to manage the circuits as we went through the stages.

Conclusion

Overall, in this project it has been question to design, construct and demonstrate a FM receiver circuit capable of demodulating and playing a single tone FM-modulated signal at 100 Hz and 1000 Hz. The FM-modulated signal was generated by the signal generator and delivered to the circuit via BNC cable. After carrying out the design, simulation, we successful built the FM Receiver circuit on the bread board. There were tremendous effort made to build the frequency discriminator because it was the first the step in demodulating the single-tone signal into AM signal, the matlab code to solve for the values of the passive elements needed in block1 did not work. Therefore, more work was done in building the actual block by constantly playing with the oscilloscope to achive the 0.7V to turn on the diode(part of the envelope detector) .
Butterworth filters appears to be better in filtering specific frequency range and that is because there are termed maximally-flat-magnitude-response filters, optimized for gain flatness in the pass-band. the attenuation is –3 dB at the cutoff frequency. Above the cutoff frequency the attenuation is –20 dB/decade/order. There was the effet of clipping encountered during this project and caused major problems in getting the message sgnal and that is because clipping in Op-Amp is when the Op-Amp cannot deliver the output voltage beyond its maximum capacity, so it does not reach the peak but instead it plateau. We also learn that a bandpass filter can be implemented by using a hghpass and lowpass filter together, thus the nice sound delivered by the speaker.

Recommendation

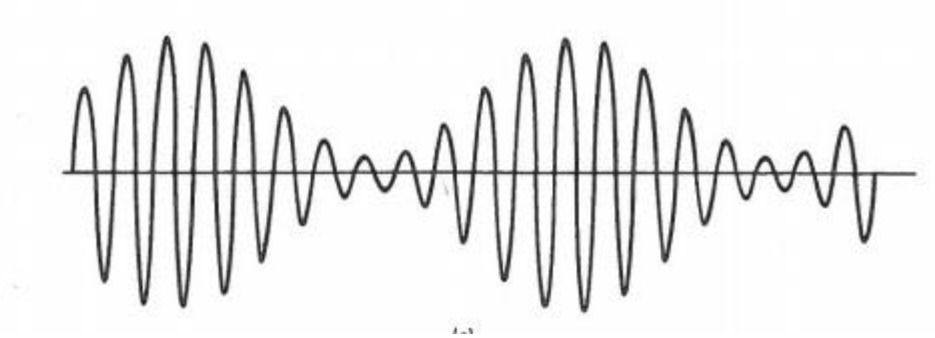
After designing, simulating and testing the FM Receiver, we can appreciate the tremendous effort done to accomplish this project, nevertheless, there are some aspects of this project that could be improved. The requirement of the project to work at 100Hz and 1kHz could be fixed to only one center frequency (bandpass with small bandwidth) to channel a radio frequency, thus enlarge the passive and active elements to operate in a building or entire the campus of the university.
Also, this project could incorporate the notion of noise cancellation.

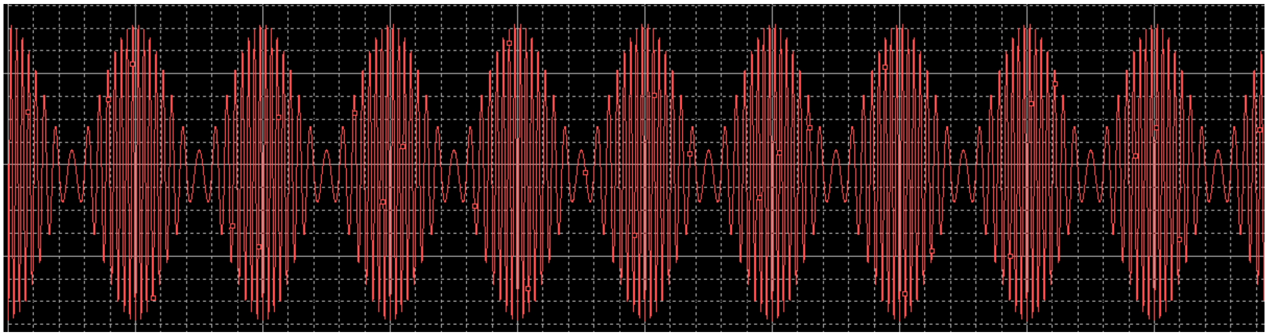
References

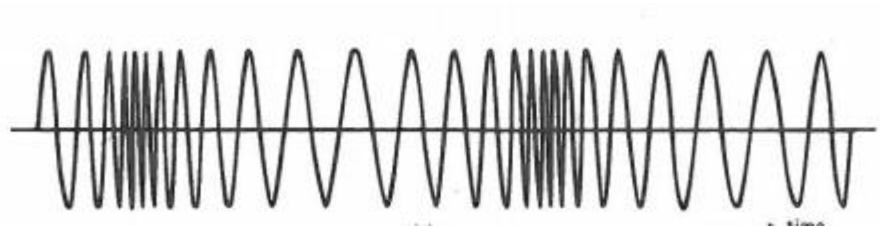
1. Nilsson & Riedel - Electric Circuits 10th Edition
2. Lawrence Der, Ph.D. Silicon Laboratories Inc. Frequency Modulation (FM) Tutorial http://www.silabs.com/Marcom%20Documents/Resources/FMTutorial.pdf
3. http://www.buzzer-speaker.com/manufacturer/magnetic%20buzzer/external/ac-1005g-p.htm
4. http://www.radioelectronics.com/info/circuits/opamp_high_pass_filter/op_amp_highpassfilter.php
5. http://sequence15.blogspot.com/2011/03/electricity-for-synth-diyers.html
6. http://www.ti.com/lit/an/sloa049b/sloa049b.pdf
7. https://learn.wsu.edu/bbcswebdav/pid-1101062-dt-content-rid-5024240_1/courses/2015-FALL-PULLM-E_E-352-3511-LEC/Class_B_amplifier.pdf
8. https://coefs.uncc.edu/dlsharer/files/2012/04/F4.pdf
9. http://www.analog.com/media/en/technical-documentation/data-sheets/OP27.pdf
10. https://www.fairchildsemi.com/datasheets/1N/1N3064.pdf
11. https://www.fairchildsemi.com/datasheets/TI/TIP31C.pdf
12. https://www.fairchildsemi.com/datasheets/TI/TIP32C.pdf

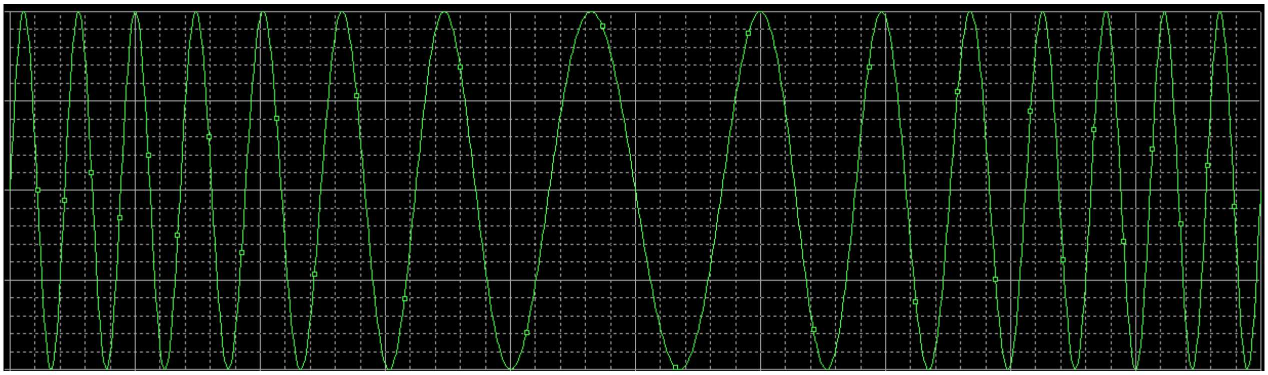
Appendices

Appendix A: AM signal





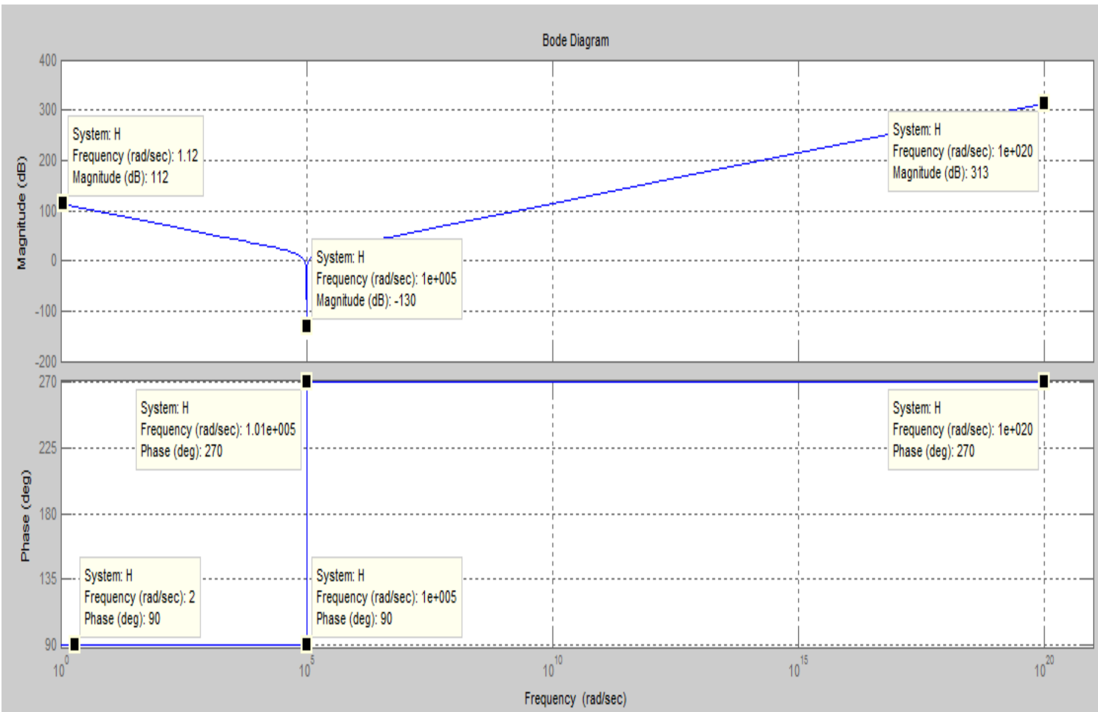


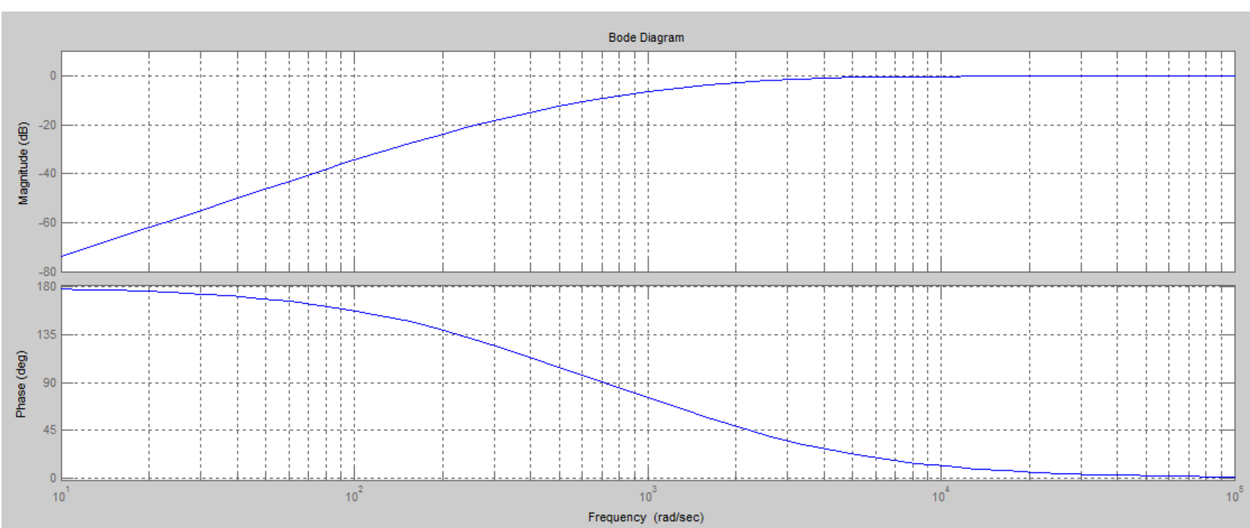


Appendix B: Matlab

Differentiator

`syms s`
`num = sym2poly(-0.000047*s*s-47e4)`
`den =sym2poly(s)`
`H=tf(num,den)`
`bode(H), grid`
Pole:
S= -100000j, 10000j
Zero :s=0
	num =
	1.0e+005 *
	-0.0000 0 -4.7000
	den =
	1 0
	Transfer function:
	-4.7e-005 s^2 - 470000
	-------------------- 	
	s





High pass filter at 100H

```
 syms s
 num = sym2poly(s*s)
den =sym2poly(s*s+2000*s+500000)
 H=tf(num,den)
 bode(H), grid
```

Pole

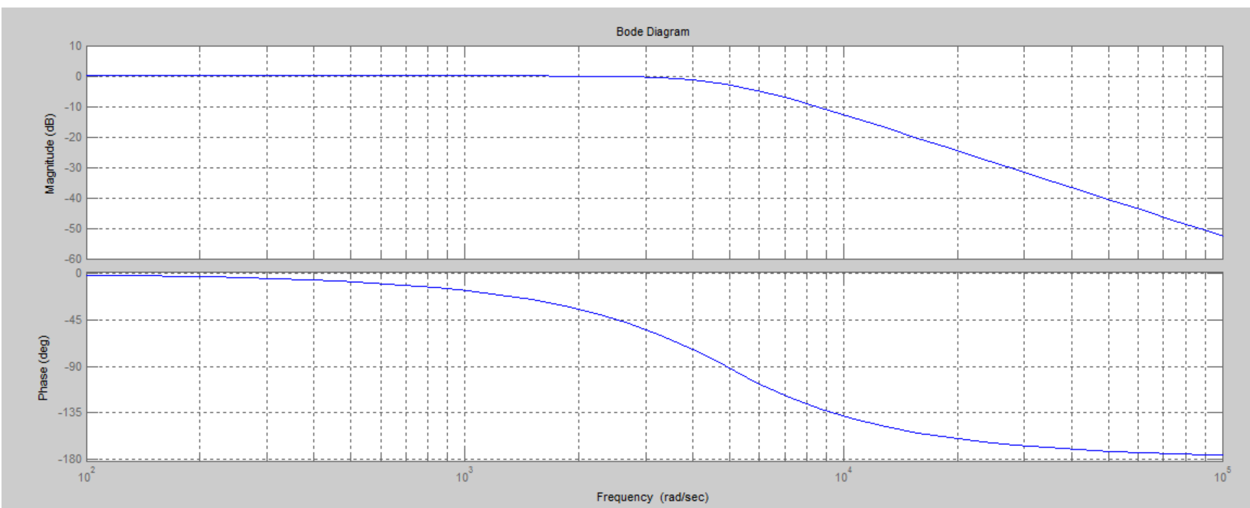
$$s = 500\left(-2-\sqrt{2}\right)$$

$$s = 500\left(\sqrt{2}-2\right)$$

Zero: s=0

```
num =
    1     0     0
den =
         1        2000     1000000

Transfer function:
       s^2
--------------------
s^2 + 2000 s + 1e006
```



LPF

```
 syms s
 num =(23640661.94)
den =sym2poly(s*s+6666.66667*s+23640661.94)
 H=tf(num,den)
 bode(H), grid
```

```
num =
  2.3641e+007
den =
  1.0e+007 *
    0.0000    0.0007    2.3641
Transfer function:
      2.364e007
-----------------------
s^2 + 6667 s + 2.364e007
```