EE 318
Electronic Design Lab

Hi-fi Audio Transmitter from first principles

Supervised by –
Prof. Jayanta Mukherjee
Prof. Dipankar
Prof. L. Subramaniam

By Group-9
Vipul Chaudhary (08d07039)
Vineet Raj (08d07040)
Samyak Jaroli (08d07041)

Table of Contents

1 Introduction ***1***

2 Frequency Modulation Background ***3***
2.1 Introduction **3**
2.2 Technical Background **3**
2.2.1 Radio Frequency and Wavelength Ranges 3
2.3 Fm theory **4**
2.3.1 Derivation of the FM voltage equation 4
2.3.2 Angle modulation Graphs 5
2.3.3 Differences of Phase over Frequency modulation 6
2.4 Technical terms associated with FM **6**
2.4.1 Capture Effect 6
2.4.2 Modulation Index 6
2.4.3 Deviation Ratio 6
2.4.4 Carrier Swing 6
2.4.5 Percentage Modulation 7
2.4.6 Carson's Rule 7
3 Electronic Components and their properties ***7***
3.1 Resistor , Inductor, Capacitor, Resonant Circuits **7**

4 Basic Building blocks for an FM transmitter ***7***
4.1 Introduction 7
4.2 Exciter /Modulator 8
4.3 Frequency Multipliers 8
4.4 Power output section 8
4.5 Pre-emphasis 9
4.6 The Oscillator 10
4.7 Driver Amplifier 10
4.8 Power Output Amplifier 12
4.9 Observations
5 Test and Results ***12***
5.1 Introduction 12
5.2 Equipment used 12
5.3 Power output 12
5.4 Frequency response 13
5.5 Distortion measure with distortion meter 15
5.6 real time testing with music audio 15
6 Final Discussion and Conclusions ***17***
6.1 Introduction 17
6.2 Report Overview 17
6.3 Discussion 17
6.4 Conclusions 17

7 Recommendations **17**

8 References **18**

1 Introduction

1.1 Abstract

In today's era of electronics and telecommunications, transmission of of audio plays a vital role. With increasing number of requirements desired from audio, 'fidelity' becomes an important aspect. Many engineers have delved deep in this topic and to achieve state-of-the-art audio transmitters and receivers. The motivation is to provide a high quality re-production of sound from first principles. This will also give us insight into Analog Electronic Design.

A **transmitter** or **radio transmitter** is an electronic device which, with the aid of an antenna, produces radio waves. Transmission can be achieved in many ways by moducation the signal over a carrier wave form. Types of Modulation Techniques include - Frequency Modulation, Amplitude Modulation, Phase Modulation etc.

The aim of this project is to design Audio transmitter which is to satisfy the following requirements:
- **Use of discrete components:** The goal of this project is to gain experience in analog electronics and design. We will maximise the usage of discrete components with minimal use of commercially available ICs.
- **Hi-Fidelity:** To obtain uniform gain and minimum noise and distortion in the audio frequency range.

The main report will reflect on 4 issues, background to frequency modulation, electronics component characteristics, basic transmitter building blocks and finally an analysis of the finished design as regards construction and performance.

2 Frequency Modulation Background

2.1 Introduction

Frequency Modulation (**FM**) conveys information over a carrier wave by varying its instantaneous frequency. This is in contrast with amplitude modulation, in which the amplitude of the carrier is varied while its frequency remains constant.

2.2 Technical Background

Frequency	*Designation Abbreviation*	*Wavelength*
3 - 30 kHz	Very Low frequency VLF	100,000-10,000 m
30 - 300 kHz	Low frequency LF	10,000 - 1,000 m
300 - 3,000 kHz	Medium frequency MF	1,000 - 100 m
3 - 30MHz	High frequency HF	100 - 10 m
30 - 300 MHz	**Very High frequency VHF**	**10 - 1m**
300- 3,000 MHz	Ultra-high frequency UHF	1m - 10cm
3 - 30 GHz	Super-high frequency SHF	10cm - 1cm
30 - 300 GHz	Extremely-high frequency EHF	1cm - 1mm

The main frequencies of interest are from 88MHz to 108MHz with wavelengths between 3.4 and 2.77 meters respectively.
With a bandwidth of 200Khz for one station, up to 100 stations can be fitted between 88 & 108Mhz. In recent years the band from 88MHz to 103Mhz has been filled by a lot of commercial channels, making the lower frequencies very congested indeed.

2.3 FM theory

Angle and Amplitude Modulation are techniques used in Communication to transmit Data or Voice over a particular medium, whether it be over wire cable, fibre optic or air (the atmosphere). A wave that is proportional to the original baseband (a real time property, such as amplitude) information is used to vary the angle or amplitude of a higher frequency wave (the carrier).

$$\text{Carrier} = A \text{ Cos } f(t)$$
$$f(t) = 2\text{pi}f_C\, t + a$$

Where A is the amplitude of the carrier and f(t) is the angle of the carrier, which constitutes the frequency (f_C) and the phase (a) of the carrier. Angle modulation varies the angle of the carrier by an amount proportional to the information signal. Angle modulation can be broken into 2 distinct categories, frequency modulation and phase modulation. Formal definitions are given below :

Phase Modulation *(PM)* : angle modulation in which the phase of a carrier is caused to depart from its reference value by an amount proportional to the modulating
signal amplitude.

Frequency Modulation *(FM)*: angle modulation in which the instantaneous frequency of a sine wave carrier is caused to depart from the carrier frequency by an amount proportional to the instantaneous value of the modulator or intelligence wave. Phase modulation differs from Frequency modulation in one important way. Take a carrier of the form $A \text{ Cos}(w_C t + q) = \text{Re}\{A.e\text{^}j(w_C t + q)\}$

FM over other modulation:
Frequency modulation has several advantages over the system of amplitude modulation (AM) used in the alternate form of radio broadcasting.
The most important of these advantages is that an FM system has greater freedom from interference and static. Various electrical disturbances, such as those caused by thunderstorms and car ignition systems, create amplitude modulated radio signals that are received as noise by AM receivers. A well-designed FM receiver is not sensitive to such disturbances when it is tuned to an FM signal of sufficient strength. Also, the signal-to-noise ratio in an FM system is much higher than that of an AM system. FM broadcasting stations can be operated in the very-high-frequency bands at which AM interference is frequently severe; commercial FM radio stations are assigned frequencies between 88 and 108 MHz and will be the intended frequency range of transmission.

2.3.1 FM voltage equation

$M_F = K * V_{pk} / f_m$

$M_F = f_c(pk)/f_m$

Setting the magnitude of the sine wave as MF , the modulation index for frequency modulation.

$V_{FM} = A \text{ Cos } q(t) = A \text{ Cos}[2\text{pi}f_c t + M_F \text{ Sin}(2\text{pi}f_M t)]$

The above equation represents the standard equation for frequency modulation.
The equation for the other form of angle modulation, phase modulation is rather similar but has a few subtle differences.
$V_{PM} = A \text{ Cos } q(t) = A \text{ Cos}[2\text{pi}f_c t + M_P \text{ Cos}(2\text{pi}f_M t)]$

The difference is in the modulation Index and the phase of the varying angle inside the main brackets.

2.3.2 Analysis of the FM and PM

The carrier, the Baseband, FM signal, PM signal and the change of frequency over time. The carrier and baseband are there to show the relative scale, so a link between the carrier and Baseband can be seen.

For FM: the carrier's frequency is proportional to the baseband's amplitude, the carrier increases frequency proportional to the positive magnitude of the baseband and decreases frequency proportional to the negative magnitude of the baseband.

For PM: the carrier's frequency is proportional to the baseband's amplitude, the carrier increases frequency proportional to the positive rate of change of the baseband and decreases frequency proportional to the negative rate of change of the baseband.

In other words when the baseband is a maximum or a minimum, there is Zero rate of change in the baseband, and the carrier's frequency is equal to the its free running value fC.
In both systems the rate of modulation is equal to the frequency of modulation (baseband's frequency).

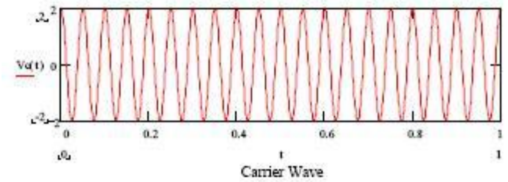


Figure 1.3-1

$$Vc(t) := A \cdot \cos(2 \cdot \pi \cdot fc \cdot t)$$

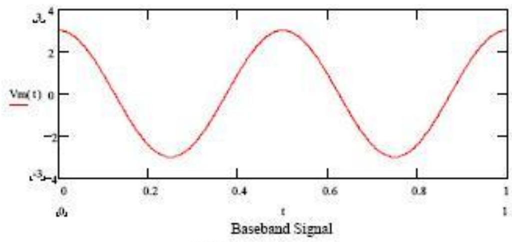


Figure 1.3-1

$$Vm(t) := (Vpk \cdot \cos(2 \cdot \pi \cdot fm \cdot t))$$

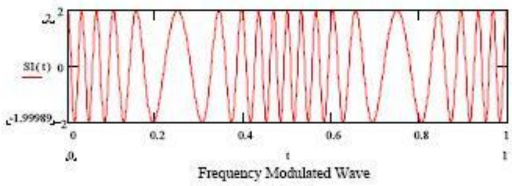


Figure 1.3-3

$$S(t) := A \cdot \cos\left(2 \cdot \pi \cdot fc \cdot t + 2 \cdot \pi \cdot Ko \cdot \int_0^t Vm(t)\,dt\right)$$

Ref - Dr. Máirtín Ó Droma, University Of Limerick

The last graph shows the relationship between the frequency of FM versus Time, this relationship is used (following a limiter which makes sure the amplitude is a constant) by a discriminator at the receiver to extract the Baseband's Amplitude at the receiver, resulting in an amplitude modulated wave, the information is then demodulated using a simple diode detector. In common AM/FM receivers for an AM station to be demodulated, the limiter and discriminator can be by passed and the intermediate frequency signal can be fed straight to the diode detector.

2.3.3 Differences of Phase over Frequency modulation

The main difference is in the modulation index, PM uses a constant modulation index, whereas FM varies (Max frequency deviation over the instantaneous baseband frequency). Because of this the demodulation S/N ratio of PM is far better than FM.
The reason why PM is not used in the commercial frequencies is because of the fact that PM need a coherent local oscillator to demodulate the signal, this demands a phase lock loop, back in the early years the circuitry for a PLL couldn't be integrated and therefore FM, without the need for coherent demodulation was the first on the market. One of the advantages of FM over PM is that the FM VCO can produce high index frequency modulation, whereas PM requires multipliers to produce high-index phase modulation. PM circuitry can be used today because of very large scale integration used in electronic chips, as stated before to get an FM signal from a phase modulator the baseband can be integrated, this is the modern approach taken in the development of high quality FM transmitters. For miniaturisation and transmission in the commercial bandwidth to be aims for the transmitter, PM cannot be even considered, even though Narrow Band PM can be used to produce Wide band FM (Armstrong Method).

2.4 Technical terms associated with FM

Now that FM has been established as a scheme of high quality baseband transmission, some of the general properties of FM will be looked at.

2.4.1 Capture Effect

Simply put means that if 2 stations or more are transmitting at near the same frequency FM has the ability to pick up the stronger signal and attenuated the unwanted signal pickup.

2.4.2 Modulation Index

$M = f_c(pk)/f_m$

(Was known as the modulation factor)

Modulation Index is used in communications as a measure of the relative amount of information to carrier amplitude in the modulated signal. It is also used to determine the spectral power distribution of the modulated wave. This can be seen in conjunction with the Bessel function. The higher the modulation index the more side-bands are created and therefore the more bandwidth is needed to capture most of the baseband's information.

2.4.3 Deviation Ratio

The deviation can be quantified as the largest allowable modulation index.

$$D_R = \frac{\Delta fc(pk)}{fm(max)} = \frac{75KHz}{15KHz} = 5 \text{ radians}$$

For the commercial bandwidth the maximum carrier deviation is 75KHz. The human ear can pick up on frequencies from 20Hz to 20KHz, but frequencies above 15KHz can be ignored, so for commercial broadcasting (with a maximum baseband frequency of 15KHz) the deviation ratio is 5 radians.

2.4.4 Carrier Swing

The carrier swing is twice the instantaneous deviation from the carrier frequency.

$F_{CS} = 2.\Delta F_C$

The frequency swing in theory can be anything from 0Hz to 150 KHz.

2.4.5 Percentage Modulation

The % modulation is a factor describing the ratio of instantaneous carrier deviation to the maximum carrier deviation.

$$\%\ \text{Modulation} = \frac{\Delta F_C}{\Delta F_{C(pk)}} \times 100$$

2.5.6 Carson's Rule

Carson's Rule gives an indication to the type of Bandwidth generated by an FM transmitter or the bandwidth needed by a receiver to recover the modulated signal. Carson's Rule states that the bandwidth in Hz is twice the sum of the maximum carrier frequency deviation and the instantaneous frequency of the baseband.

Bandwidth = $2\,(\Delta F_C\,(pk) + F_M)$

$= 2\,F_M\,(1 + M_F)$

3 Electronic Components and their properties

3.1 Resistor, Inductor, Capacitor, Resonant Circuits,

Trimmer Capacitor - Polypropylene capacitors are ideal variable capacitors, with a range of 2pF to 22 pF were used.

Self Made Inductors - can be easily wound around air cored formers, there are a number a various manufactured air cored formers on the market. Self made inductors are very useful when a particular inductance is desired.

$$L = N^2\left(\frac{d^2}{18d + 40b}\right)$$

where L = inductance in mH

d = diameter, in inches

b = coil length, inches

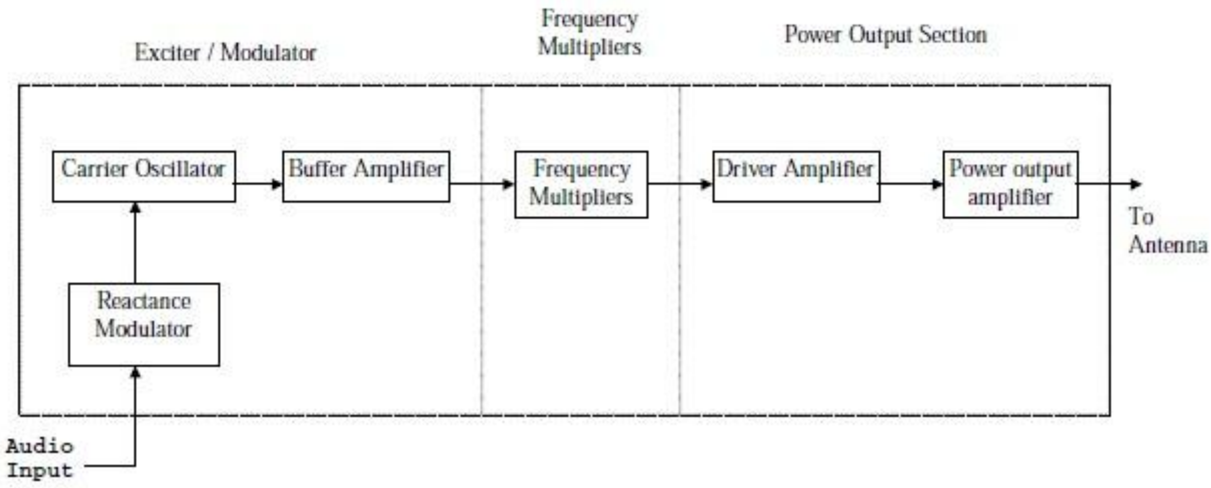
N = number of turns

$$N = \frac{\sqrt{L(18d + 40b)}}{d}$$

4 Basic Building blocks for an FM transmitter

4.1 Introduction

When creating a system for transmitting a frequency modulated wave a number of basic building blocks have to be considered, the diagram below gives a very broad Impression of the transmitter and it's individual parts.



4.2 Exciter /Modulator

- Carrier Oscillator generates a stable sine wave for the carrier wave. Linear frequency even when modulated with little or No amplitude change
- Buffer amplifier acts as a high impedance load on oscillator to help stabilise frequency.
- The Modulator deviates the audio input about the carrier frequency. The peak + of audio will give a decreased frequency & the peak - of the audio will give an increase of frequency

4.3 Frequency Multipliers

- Frequency multipliers tuned-input, tuned-output RF amplifiers. In which the output resonance circuit is tuned to a multiple of the input .Commonly they are *2 *3*4 & *5.

4.4 Power output section

- This develops the final carrier power to be transmitter. Also included here is an impedance matching network, in which the output impedance is the same as that on the load (antenna).

4.5 Pre-emphasis

Improving the signal to noise ratio in FM can be achieved by filtering, but no amount of filtering will remove the noise from RF circuits. But noise control is achieved in the low frequency (audio) amplifiers through the use of a high pass filter at the transmitter (pre-emphasis) and a low pass filter in receiver (de-emphasis). The measurable noise in low-frequency electronic amplifiers is most pronounced over the frequency range 1 to 2KHz. At the transmitter, the audio circuits are tailored to provide a higher level, the greater the signal voltage yield, a better signal to noise ratio. At the receiver, when the upper audio frequencies signals are attenuated t form a flat frequency response, the associated noise level is also attenuated.

4.6 The Oscillator

The carrier oscillator is used to generate a stable sine-wave at the carrier frequency, when no modulating signal is applied to it. When fully modulated it must change frequency linearly like a voltage controlled oscillator. At frequencies higher than 1MHz a Colpitts (split capacitor configuration) or Hartley oscillator (split inductor configuration) may be deployed. A parallel LC circuit is at the heart of the oscillator with an amplifier and a feedback network (positive feedback). The Barkhausen criterion of oscillation requires that the loop gain be unity and that the total phase shift through the system is 360_o. I that way an impulse or noise applied to the LC circuit is fed back and is amplified (due to the fact that in practice the loop gain is slightly greater than unity) and sustains a ripple through the network at a resonant frequency of 1/2p LC Hz.

The Barkhausen criteria for sine-wave oscillation maybe deduced from the following block

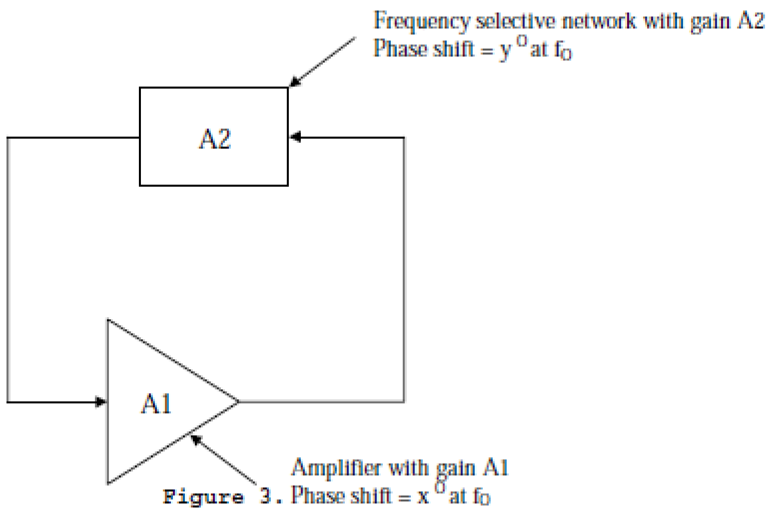


Figure 3.

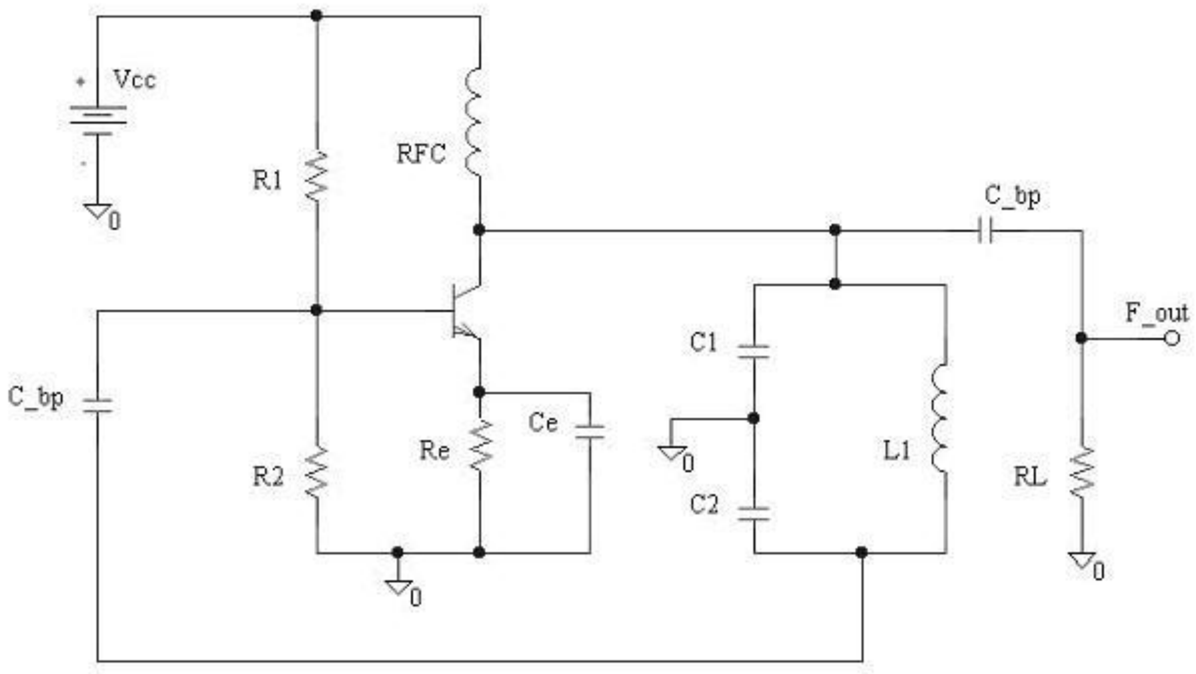
diagram

Condition for oscillation

$x_o + y_o = 0_o$ or 360_o

Condition for Sine-wave generation

A1 * A2 = 1



The above circuit diagram is an example of a colpitts oscillator, an LC (L1, C1 &C2) tank is shown here which is aided by a common emitter amplifier and a feedback capacitor (C_fb) which sustains oscillation. From the small signal analysis in order for oscillation to Kick off and be sustained.

Gm*RL= C1/C2 the frequency of the oscillator is found to be 1/(2*pi*√LC*), where C* is C1*C2/(C1+C2)

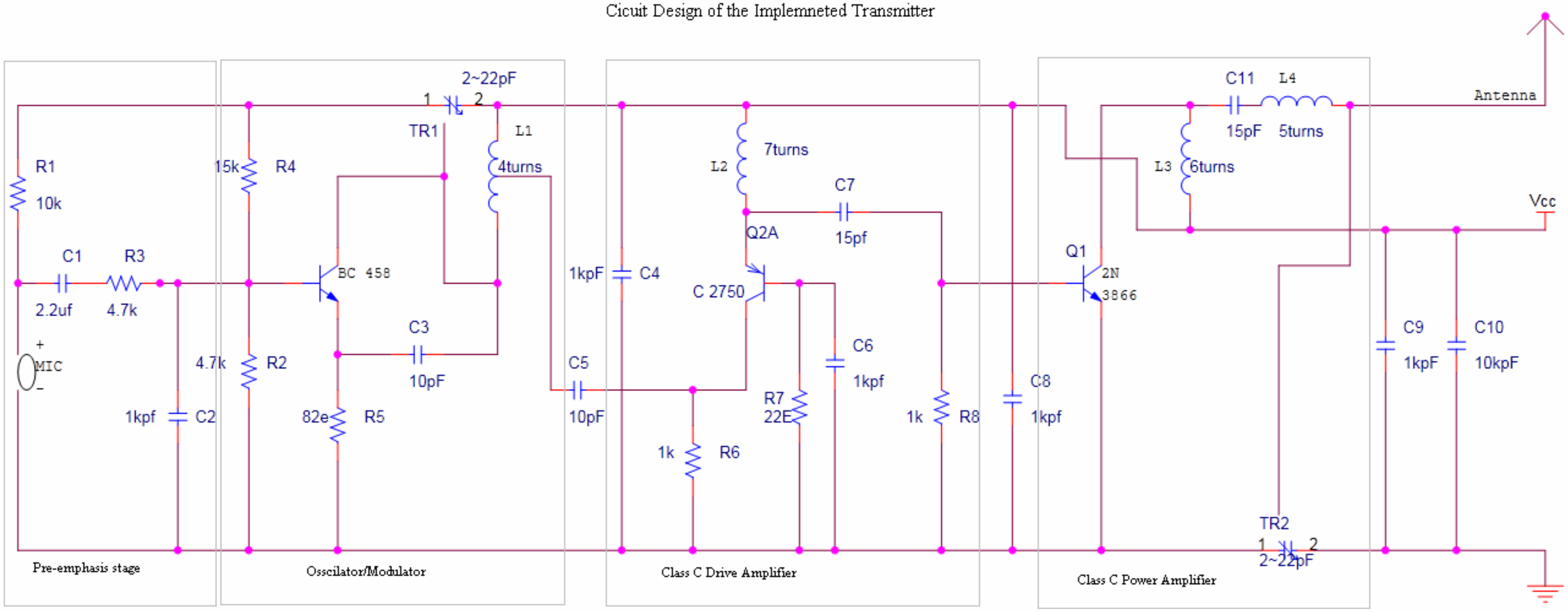
4.7 Driver Amplifier

The driver amplifier can be seen to do the same function as the buffer amplifier, i.e. a high input impedance, low gain (close to unity) and low output impedance between the frequency multiplier and power output stages of the transmitter.

4.8 Power Output Amplifier

The power amplifier takes the energy drawn from the DC power supply and converts it to the AC signal power that is to be radiated. The efficiency or lack of it in most amplifiers is affected by heat being dissipated in the transistor and surrounding circuitry. For this reason, the final power amplifier is usually a Class-C amplifier for high powered modulation systems or just a Class B push-pull amplifier for use in a low-level power modulated transmitter. Therefore the choice of amplifier type depends greatly on the output power and intendedrange of the transmitter

Cicuit Design of the Implemneted Transmitter



4.9 Observations:

- Oscillator frequency and its harmonics were obtained in the spectrum analyser.
- The oscillator frequency i.e. the first harmonic can be tuned between the range of 70-120 MHz depending upon the value of the variable capacitor
- We can vary the power of the output signal by varying the value of the capacitor in the Power Amplifier stage.
- Maximum Power we could obtain was for 98.9 MHz at -15dB.
- We used a standard receiver to test the circuit, which was able to auto-tune to our frequency and the quality of sound obtained was very much satisfactory.

5 Test and Results

5.1 Introduction

This section will discuss some of the more detailed tests carried out on the final circuit which was discussed earlier. Graphs and pictures will be used to aid in the analysis of the Design.

5.2 Equipment Used

The equipment used in analysing circuitry is vital in yielding the correct information about the advantages and disadvantages of any design. During the course of final test the equipment used were a spectrum analyser, digital multi-meter, an Analog FM radio receiver and phone as digital FM Receiver were used. We also gave sinusoidal and audio input from the Laptop using 3.5mm Jack.

5.3 Power Output

The input voltage given to the circuit could be from 5 to 12 Volts.

Supply Voltage (Volts)	Supply Current (mA)	Power (mW)
5	10.9	54.5
6	15	90
7	18.06	126.42
8	22.7	181.6
9	27.1	243.9
10	34.4	344
11	42.1	463.1
12	48.1	577.2

Spectrum Analyser

A spectrum analyser shows the frequency response over a specified width in the frequency domain. The spectrum analyser was used to view the carrier frequency and the signal strength. We also observed the almost negligible effect of modulating signal on the frequency response.

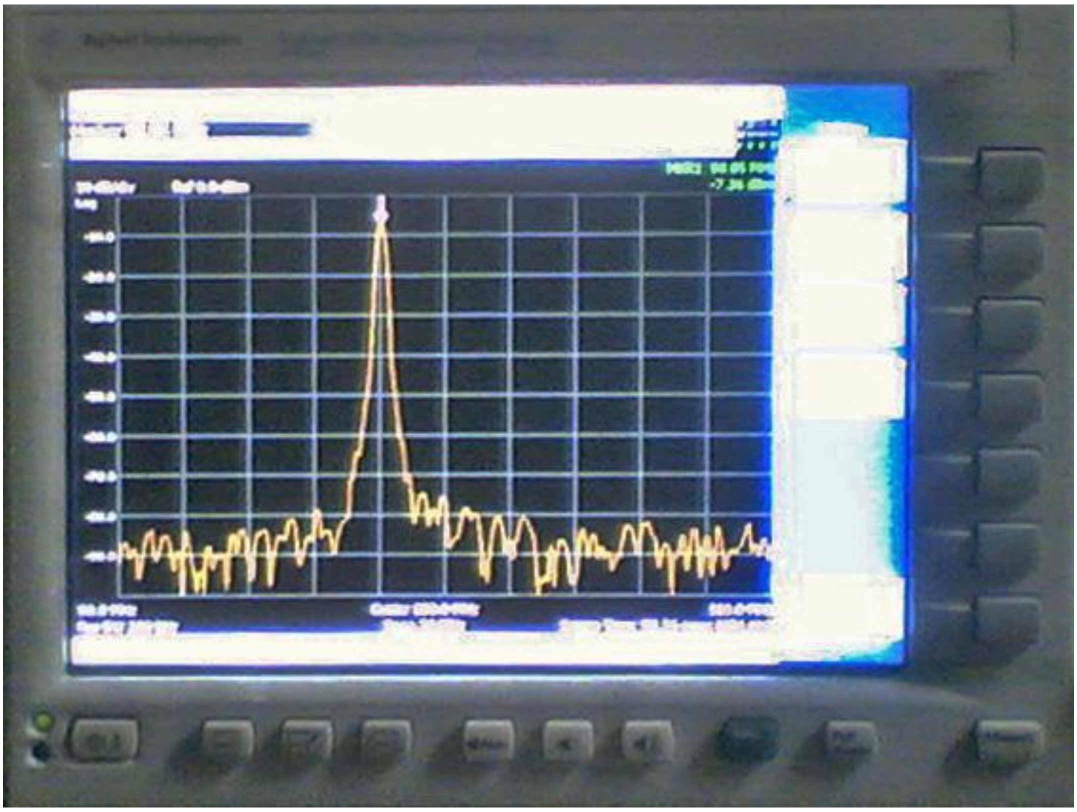


Fig. Spectrum analyser - frequency response of modulated signal. We can see a clear peak at 98.9 MHz, i.e. the carrier frequency, with -15 dB amplitude.

5.4 Frequency Response

Another important parameter for measuring the performance and fidelity of the circuit is the frequency response. Tones of discrete frequencies ranging from 100 Hz to 20 KHz were given as input and the output amplitude was measured as follows

Frequency	Output (mv)
100	280
126	280
150	280
200	260
250	200
275	170
300	150
325	128
350	120
400	112
500	108
600	112
700	120
800	138
900	140
1000	144
1100	148
1200	190
1300	210
1500	230
1800	240
2000	250
2200	250
2400	235
2600	220
2800	210
3000	225
3200	215
3400	210
3600	210
3800	205
4000	200
4200	195
4400	185
4600	180
4800	170
5000	165
5200	165
5400	165

Next we used a chirp input with frequencies ranging from 100 Hz to 20 KHz and took the output from the FM receiver into Audacity - a computer software - to measure the frequency response of the system.

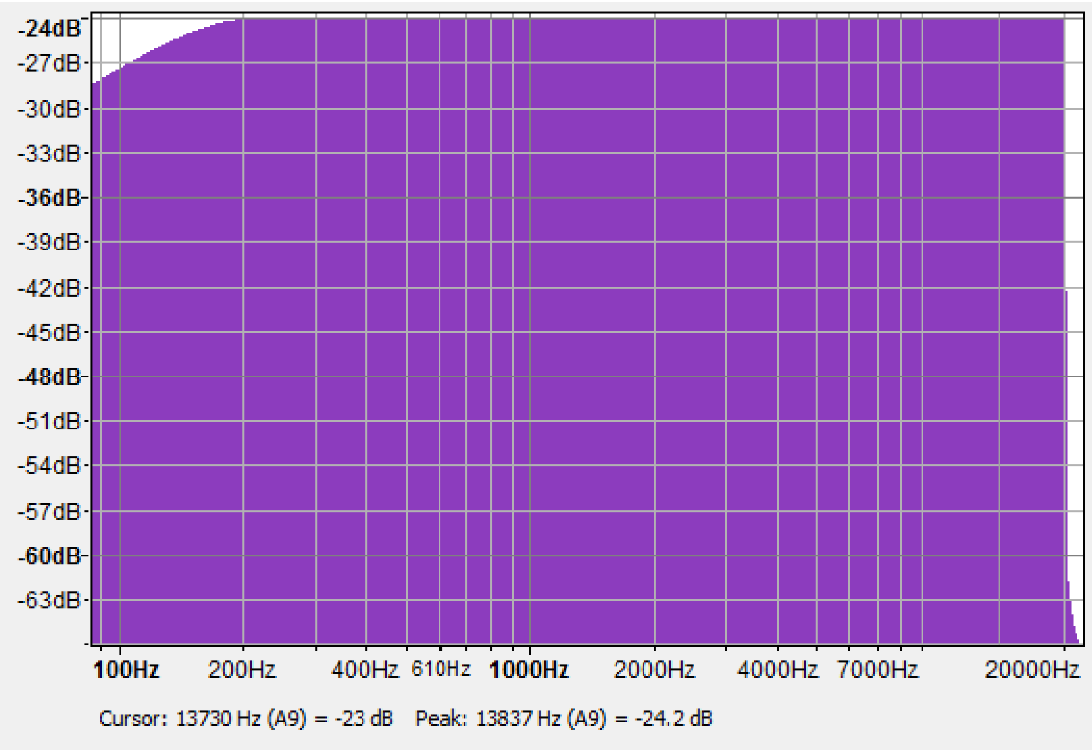


Fig. Chirp input. Frequency varies from 100 Hz to 20 KHz

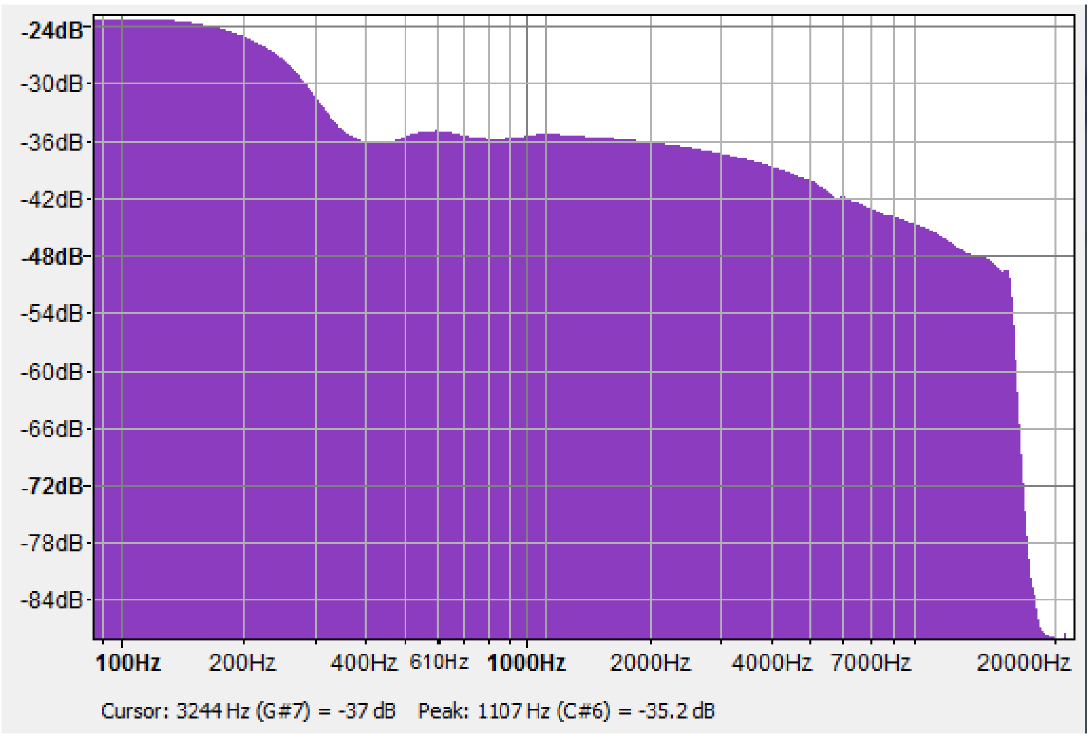


Fig. Output to the chirp input with frequencies varying from 100 Hz to 20 KHz. A dip at 400 Hz and then a 10dB/decade roll off observed

From the output, it can be seen that the output amplitude is almost equal for the speech frequency range i.e. 400 Hz to 6000 Hz. There is a sharp fall in the output at around 15KHz, that is because of the sampling frequency limitation in the digital FM receiver.

Frequency response of a chirp signal shows us the performance of our circuit for various input frequencies.

5.5 Distortion Measure with Distortion Meter

We used the 400 Hz and 1000 Hz distortion meter available in the lab. Using the signal generator a 400 Hz sine wave was given as input to the circuit. The output of the FM receiver was again given to the distortion meter and we got the distortion as 6.4 %.

5.6 Real Life Testing with Music Audio

We played a music file and gave it as an input to the transmitter through a 3.5 mm jack.
The following are the frequency domain plots of the input and the output and is followed by a superimposed comparison.

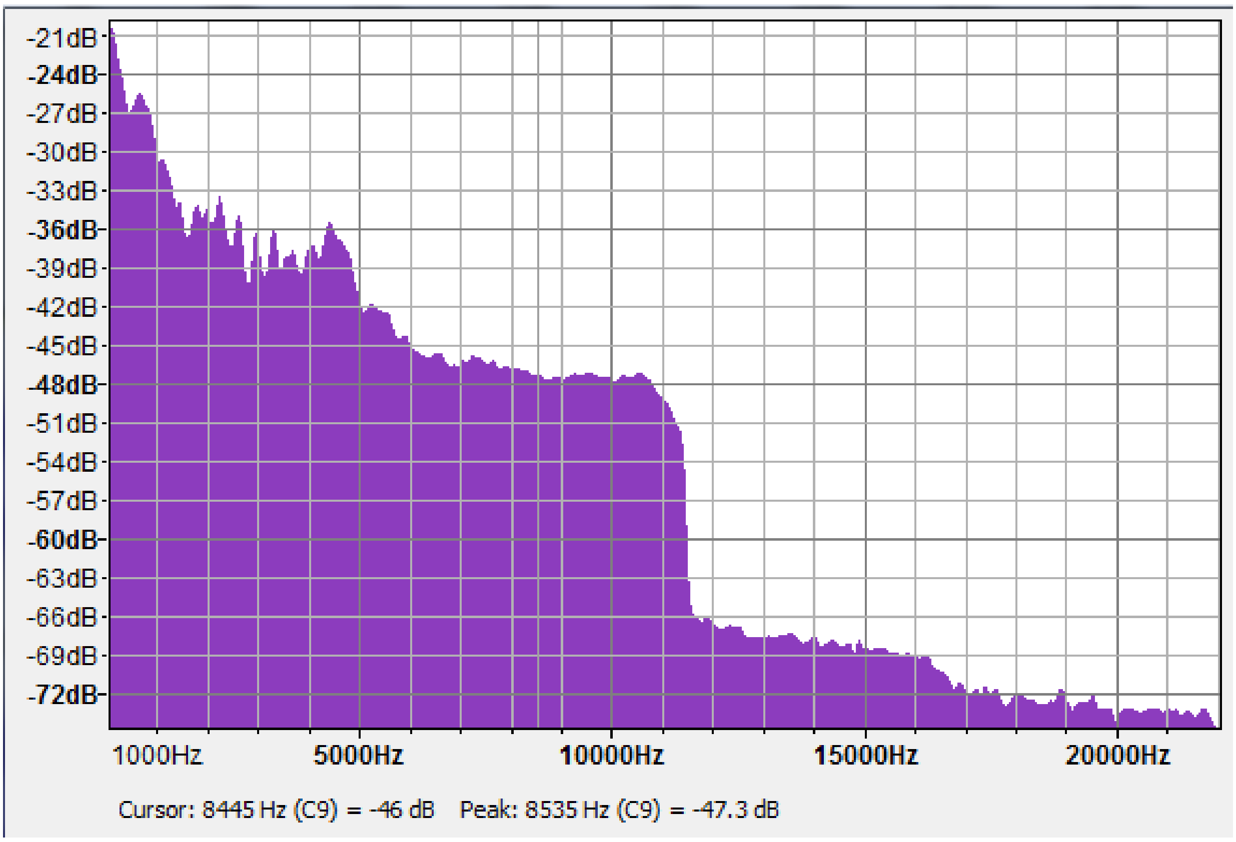


Fig. Frequency domain plot of the original song file.

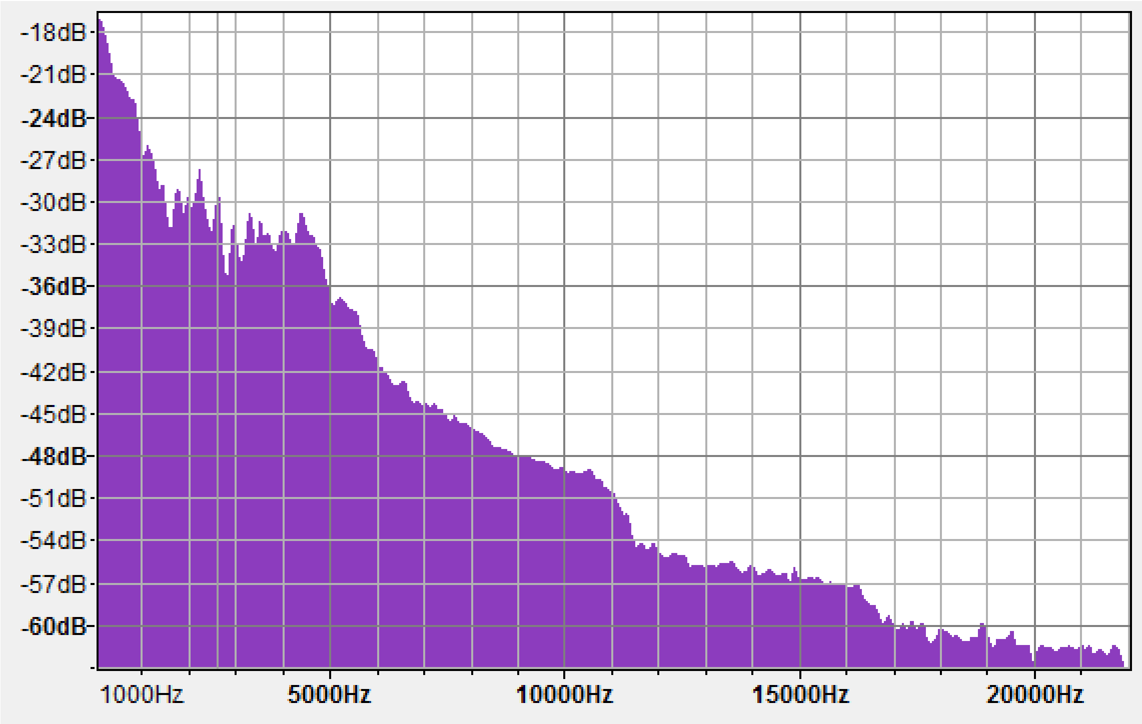


Fig. The frequency domain plot of the output from FM receiver.

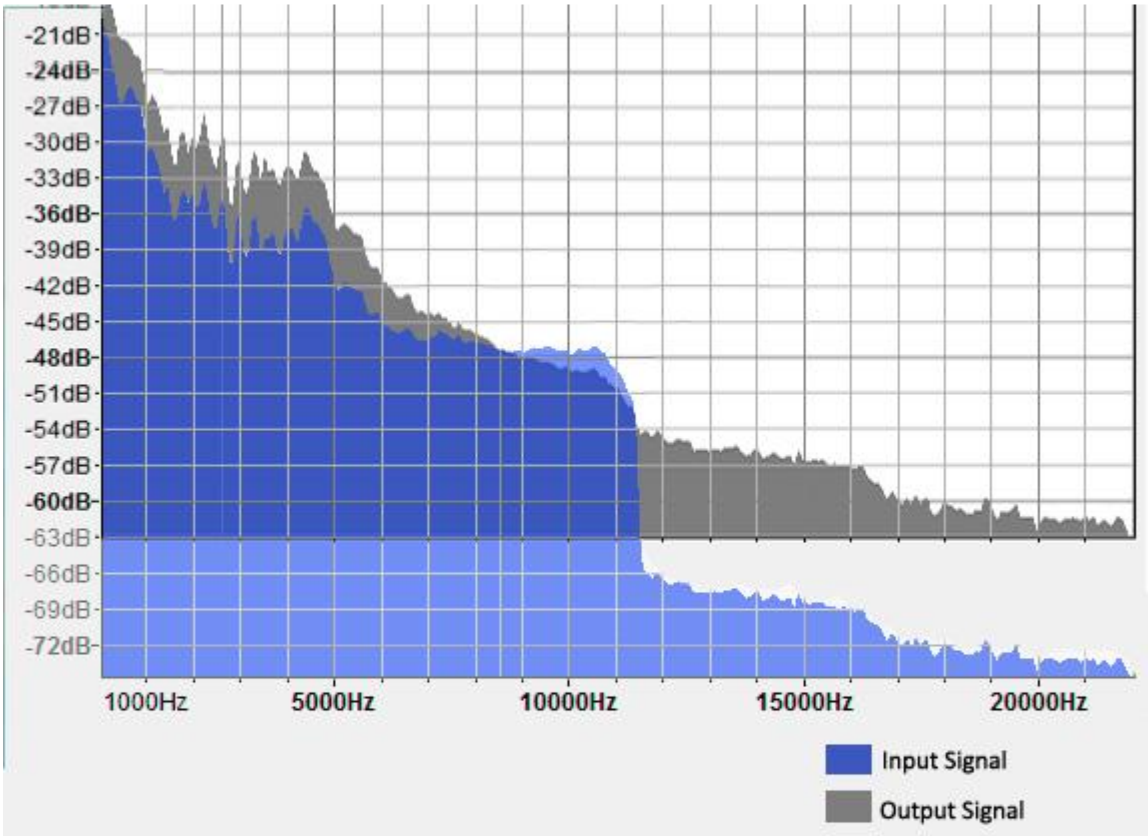


Fig. Comparison between the frequency domain plots of input and output music signals.

6 Final Discussion and Conclusions

6.1 Introduction

The fundamental aim of this project was to design an Audio Transmitter with High fidelity from first principles. This final section shall begin with a detailed discussion of the main topics from initial approach to final design and implementation. Also in this section a number of conclusions shall be drawn from the approach.

6.2 Report Overview

When considering a design for frequency modulation, a number of key elements have to be considered, such as a good understanding of the concept of modulation schemes and the electronic circuitry that goes into creating the scheme.

In earlier sections of this report the theory of frequency modulation was covered, and then a broad overview of electronic components and their various properties were considered. We discussed the various building blocks and considered their possible use in the final design. A detailed description of how each block works is given here, along with approach to choose the design.

Finally the results of the various tests used on the design and observations and inferences were presented.

6.3 Discussion

The design chosen was miniature, and tuneable to different frequencies.

The parts used are very common and the circuit is very easily constructed. The circuit was firsts PCB, as expected performed exceedingly well, but more of a better attempt had to be made in matching the antenna and shielding the RF section from the output as the PCB layout was a lot more efficient in radiating power out. Unwanted Electro-magnetic radiation had to be stopped from destructively interfering with the carrier modulation.

The effective range of the transmitter was 80 feet in a household environment and about 50 feet in a lab environment.

6.4 Conclusions

The High Fidelity Audio transmitter is essentially a Design and Implementation project.

To approach a project like this a parallel path has to be taken in regards to the Theory and the practical circuitry, for a successful conclusion in any project these paths must meet, and this only happens when they are fully understood. This is why a good grounding in the basics of Communication theory and Analog design must be achieved before ever approaching a project like this. To start off looking at block diagrams of basic transmitter was a must, even if it seemed abstract and obscure the underlying meaning of each block can be found out one by one. The Aim to make it using first principles i.e. without the use of modules or ICs made the overall project challenging and rewarding.

7. Recommendations

The design used for this project is essentially quite a simple one, and it is this simplicity which partly brings it down when it comes to the overall reliable performance. The main area of problems is the ambient noise in the in the transmitted signal.
After learning a lot from this project, there would have been a few things that could have been done to the final design to improve its performance.

- Design could have a higher input swing for acceptance of larger amplitude of input voltages
- Shielding the oscillator part using aluminium foil will prevent any stray signal feedback from interfering with modulation.

8. References

1. Communication Systems, by Haykins.
2. Wikipedia, pages on Colpitts Oscillator, Frequency Modulation etc.
3. Electronic communications: modulation and transmission / Schoenbeck, Robert.
4. Electronic devices / Floyd, Thomas L.