IMPLEMENTATION OF FULL DUPLEX RADIO

A Project Report

submitted by

ALTHAF YOOSUF

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THESIS CERTIFICATE

This is to certify that the thesis titled **Implementation of Full Duplex Radio**, submitted by **ALTHAF YOOSUF**, to the Indian Institute of Technology, Madras, for the award of the degree of **MASTER OF TECHNOLOGY**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr.Radhakrishna Ganti
Project Guide
Assistant Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai

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ABSTRACT

KEYWORDS: Full Duplex, Self Inteference, Analog RF Cancellation

In this thesis, the design and implementation of full duplex transceiver as well as the other support systems for it are discussed .In Full Duplex systems, for effective noiseless communication it is necessary to have good self-interference cancellation of transmitted signal to noise floor ,(which is 120 dB for an OFDM Signal of peak power 30 dBm and noise floor -90dBm). Achieving this cancellation becomes challenging due to group delay, phase noise, quantization noise , I-Q imbalance ,non-linear effects etc. which all happen due to self-interference .These problems are resolved using the analog cancellation in RF domain which condition the signal to counter these effects. It is also found that with the analog cancellation achieved, the signal is now be exposed to more self-interference in base-band domain since the self-interference signal ,received signal, and noise floor all lie within the dynamic range of ADC.

Required analog cancellation is achieved using self-cancellation board developed at our institute which provides around 30 dB of isolation and the remaining cancellation is attained by feeding from dummy port the cancellation signal in analog generated by changing attenuation and phase through vector modulators and external attenuators which gives us a total of 60 dB of cancellation.So the thesis content is mainly the evaluation board design and implementation of the blocks involved in analog cancellation side.

Contents

List of Figures

ABBREVIATIONS

VM	Vector Modulator
PD	Power Detector
LPF	Low Pass Filter
BAL	Balun Transformer
DAC	Digital to Analog Converter
TI	Texas Instruments
AD	Analog Devices
DRC	Design Rules Check
BB	Base Band
RF	Radio Frequency

NOTATION

Fc	Cut-off frequency
α	Attenuation
β	Phase Constant
Zo	Characteristic Impedance
$VSWR$	Voltage Standing Wave Ratio

Chapter 1

INTRODUCTION

Generally, wireless communication systems are half duplex. They cannot transmit and receive at the same carrier frequency at the same time. The signal from the transmitting antenna is hundreds of thousands stronger than the received signal. This is because the signal transmitted from a node attenuates quickly over distance and when a signal reaches the receiving node, it will be very weak. The received signal contains both the desired signal and the strong interference from the transmitting antenna of the same node. Thus the desired signal cannot be decoded at a wireless node while it is simultaneously transmitting.

It is possible to build a full duplex system with an antenna each for receiving and transmitting. The receiving antenna provides the desired signal as well as the interference coming from the transmitting antenna. Since we know the transmitted signal from the node, we can subtract the transmitted signal content from what is received at the receiving antenna, thus canceling the self interference and making the decoding of the desired signal possible.

1.1 Origin of self-interference

The signal coming into the receiver of a full duplex system will have not just the intended received signal but also many copies of the transmitted signal coming through various paths. These paths arise because of the following reasons:

1) Transmitter and receiver coupling at the antenna.

2) Leakage of the transmit signal from the power amplifier to the receiver.This can happen via the printed circuit board (PCB) substrate (for a system implemented on a board) or the silicon substrate (for a system implemented on an integrated circuit).

So the aim is to cancel its own interference (self interference) through the various analog and digital cancellation techniques(Sahai et al., 2012).Various methods have been applied to cancel the self interference, which began from using three antennas (Choi et al., 2010) down to two antennas and now at single antenna.The different models for full duplex have been analyzed in depth for analytic results (Sahai et al., 2012) which tells the limitation for the different techniques.Thereafter the recent technique is reported to be achieve cancellation of around 110dB, which brings down the signal to the level of noise oor by modeling the interference at analog and digital levels.The basic idea could be represented through the following figure :

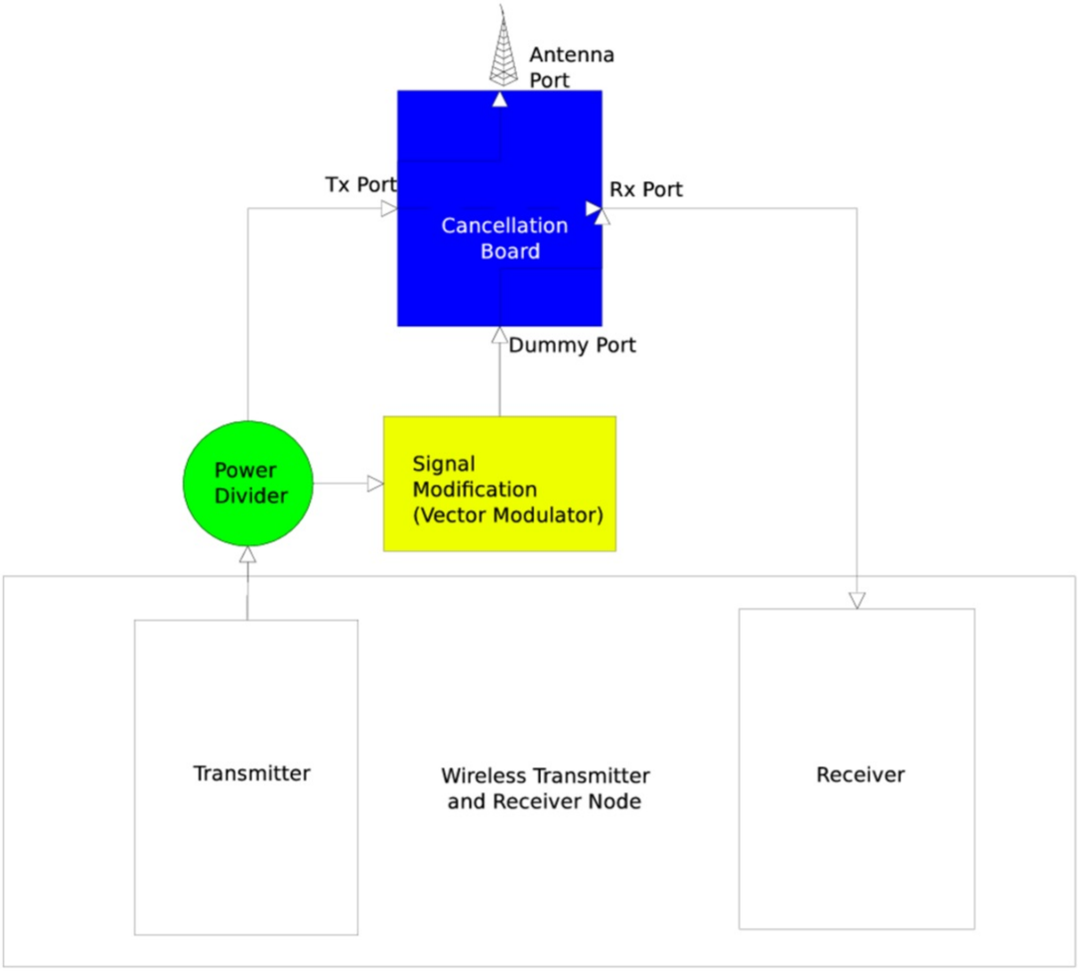

Figure 1.1: Basic Block Diagram

Cancellation Technique has been explained in Chapter 2.It takes input from Tx port and transmits it from antenna through Antenna port.Received signal from antenna goes to Receiver port.Cancellation signal is given through Dummy port. Here if the SI is canceled in analog domain through modeling the cancellation in digital domain,it is referred to as base band analog cancellation and if the cancellation signal is extracted and varied in analog domain after transmission then it is referred to as RF analog cancellation.It is observed that due to various effects(non-linearity,phase noise of analog circuits like power ampliers,oscillators) we are not able to achieve required amount of cancellation for base-band,solely using analog cancellation. Analog domain cancellation becomes important due to two main factors: 1)Limited Dynamic Range of ADC's : Due to limited dynamic range of ADC's,the required signal could get vanished in the quantization errors before ADC decent minimum cancellation is required in analog domain. 2)Due to random nature of noise in the RF domain which arises from high power components,it could to lead to complete distortion of received signal so should be tapped out and canceled in analog domain(Bharadia `et al., 2013`). So for achieving full cancellation, RF cancellation technique is applied and it achieves around 60dB of cancellation for the main component path.But in the real wireless environment as we transmit through the antenna,antenna mismatch and multipath component also arises which also consists of significant power and must be canceled.For that, we plan to increase the robustness of the technique to handle those path also giving sufficient amount of analog cancellation.

The following chapters deals with challenges we face in full duplex, the cancellation techniques in detailed , followed by various blocks used in implementing full duplex radio and the final design which I did.

Chapter 2

RF Cancellation Techniques

An ideal full-duplex communication system has double the usable bandwidth in a bi-directional link. However, self-interference is a major impediment in realizing a full-duplex system as the much stronger transmit signal drowns the received signal and in the process saturates the receiver chain. In the past few years, there has been renewed efforts in building an ideal full-duplex system

In a two antenna system, antenna separation is a simple way of providing passive isolation between the transmit and the receive chains. The isolation depends on the separation distance between antenna, orientation and polarization. In general, the isolation can be upwards of 40 dB. However, we focused on shared antenna architecture wherein a single antenna is used for both transmission and reception.The entire transmit chain is replicated for generating a duplicate copy of the self-interference signal for cancellation. However, the additional RF chain introduces noise, and canceling the non-linearity introduced by the Power Amplifier in the transmit path is much more difficult. A common technique for RF self-interference cancellation in shared antenna architectures is to use a multi-tap RF filter with fixed delay lines and tunable gains. We have used sixteen RF delay lines with variable gains to lter the known RF signal. The delays (in the range of 400 ps to 1.4 ns) were permanently tuned to the strongest self-interference paths through the PCB and the antenna. An RF cancellation of about 60 dB is reported (in conjunction with a circulator).A three-path RF lter using vector modulators is implemented. Also, the control logic of the vector modulators is implemented in the analog domain and an RF cancellation of 60 dB for 20 MHz is reported. This technique of implementing an RF lter (tap delay line lter) has the following disadvantages:

- It requires multiple delay lines, and achieving delays at high frequencies in the RF domain is extremely difficult.
- It is difcult to realize such a multi-tap RF lter in a small form factor.
- The RF lines have to be carefully tuned a priori and the resulting circuit might not work effectively if the reflectors and the self-interference paths change substantially.

A 35-40 dB passive isolation was reported using hybrid transformers and a vector modulator. An electrical balance tunable RF network was used to provide an isolation of greater than 50 dB in the RF domain with a combination of active and passive techniques.

In summary, the passive isolation techniques (separation of antenna, circulator) can provide about 40 dB isolation,the active cancellation techniques provide about 35-40 dB isolation providing the total RF isolation to be about 65-70 dB for 20 MHz bandwidth.

2.1 Baseband digital cancellation

Digital base-band cancellation consists of removing the residual self-interference after RF and base-band analog cancellation.The SI channel is estimated using a least-squares technique and the SI is canceled using the estimated channel and the known transmitted signal. However, these techniques incur significant complexity since the entire channel (with unknown number of taps) has to be estimated constantly to track the channel changes due to the varying reflections. The importance of removing the nonlinear components of the signal are highlighted and 45 dB digital cancellation was reported. Other implementations have reported about 30 dB cancellation. It has been shown that the limited dynamic range of the analog to digital conversion is a bottleneck in effective cancellation of self-interference in the digital domain. In all these digital techniques, no prior model of the lter (for the linear components) is used leading to a higher implementation complexity. Digital cancellation leads to about 35-40 dB of self-interference suppression for most of these designs.

2.2 Baseband analog cancellation

An analog cancellation technique is proposed in conjunction with an antenna design. However, the gains of the analog cancellation in isolation are not clear. Analog cancellation techniques while recognized as important, are not common because of the restricted access to the base-band signals in commercial off-the-shelf (COTS) equipment. In baseband analog cancellation, a sinusoid is transmitted from a USRP and the cancellation signal is generated in baseband from another USRP and fed to the dummy port.Now the amplitude and phase of the signal is adjusted such that it matches in amplitude and is of opposite phase.For any signal,addition of both SI signal and cancellation signal produces a null at receiver.In practice for single tone signals this method works quite well but for multi-tone signals (or as bandwidth is increased), the cancellation achieved is decreased due to various effects of group delays, nonlinearities, IQ imbalance, phase noise, etc.. All these effects limits the cancellation and therefore the required cancellation is not achieved.So to counter these effects and for achieving required cancellation, RF analog cancellation methods are explored.

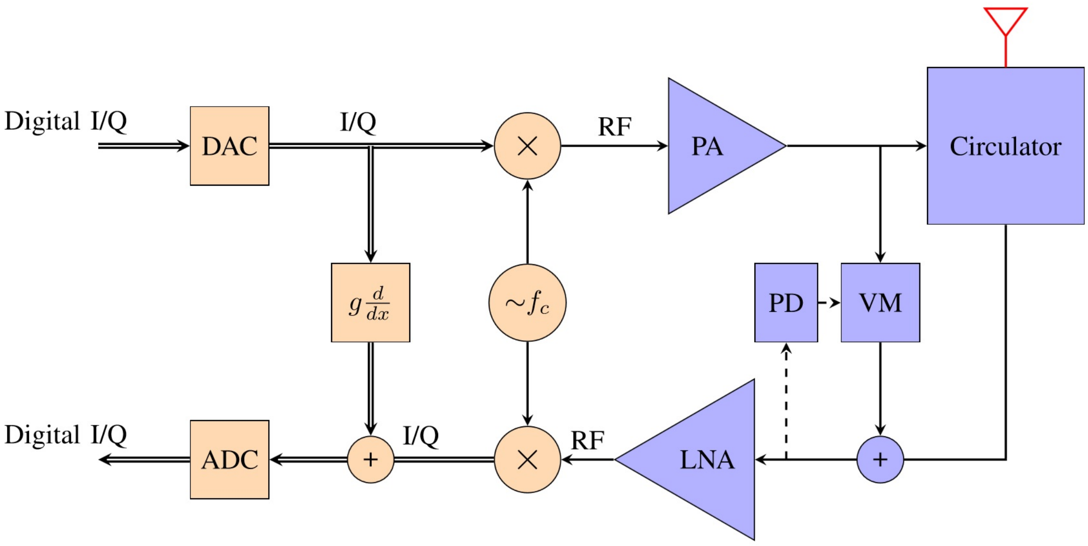

Figure 2.1: Canceling Id(t) in the analog domain. The derivative canceler is implemented in the analog domain after down conversion and before the ADC

2.3 RF Analog Cancellation

Here the cancellation signal is acquired as a tap from the transmitted signal and is then amplitude and phase shifted in the RF domain to match the self interference(consisting of transmitted signal leakage component from Tx to Rx port,antenna reection and various multipaths).

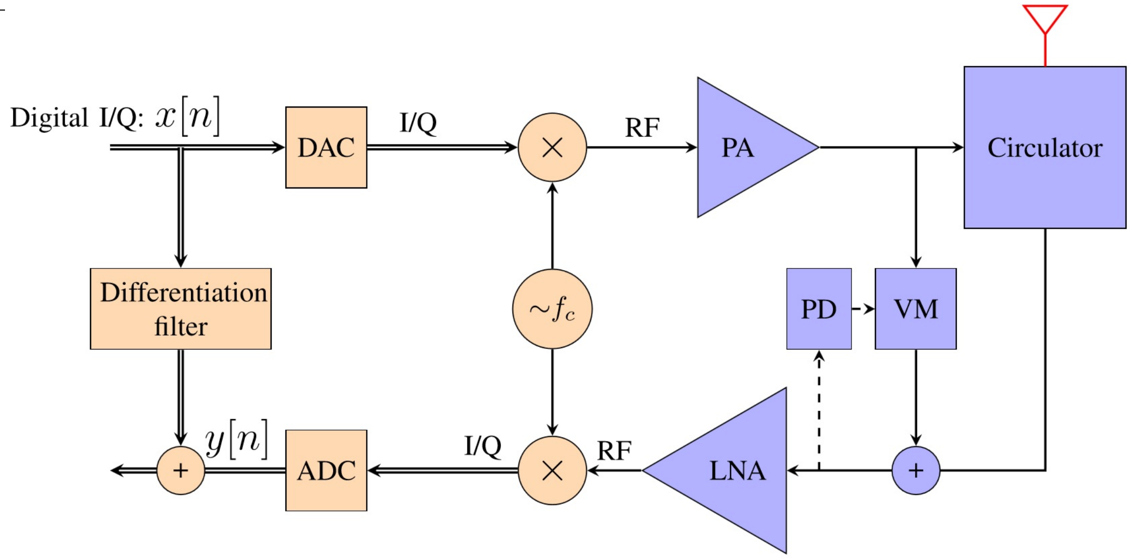

Figure 2.2: Cancellation architecture. We cancel Is(t) in the RF domain and Id(t) in the digital domain

2.4 Required amount of cancellation for full duplex

Based on above analysis and the results from different previous works(Bharadia et al., 2013), (Sahai (et al., 2012)) considering transmit power to be of 20dBm as of WiFi, the total amount of cancellation required comes out to be 110dB to set it to noise oor and out of that at least 60dB must be achieved in analog domain and rest to be done in digital domain.Since the various effects caused by analog circuits which are random or complex in nature(therefore can't be modeled analytically) have the power owing to excess of around 60dB above noise oor so theym ust be canceled in analog domain.Also considering dynamic range of ADC to be 72dB (12bits),it turns out that if 60dB in analog is achieved then received signal is totally prevented from distortion due to quantization error.

Chapter 3

Block Diagram and Implementation

The block diagram for the implementation of interference cancellation is given in the Fig. 3.1. The block diagram contains a Balun, Vector Modulator, a Power Combiner ,Power Detector and support components.

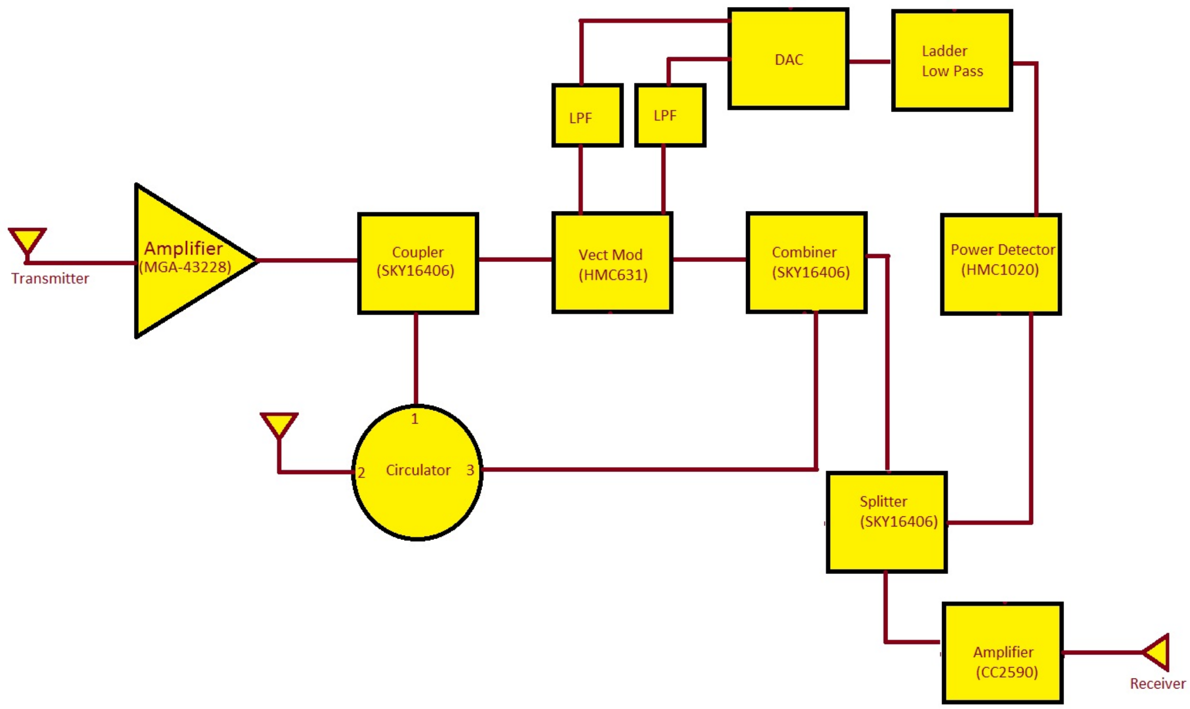

Figure 3.1: Block diagram of full Duplex Radio

3.1 Vector Modulator

It is used to change the gain and phase of the cancellation signal to match the SI signal.It works in the principle that the input signal to VM is divided into in-phase and quadrature component and then they are attenuated by different amounts such that they combine to produce a required phase shift.Also an external attenuator can be installed which varies its attenuation such that the total attenuation of the circuit matches the required one.

3.1.1 Evaluation Board

The main IC become functional only with support from various passive and active components.So we have to make the layout for this on PCB, following the track width, ground spacing, substrate thickness, dielectric constant of the material used etc.

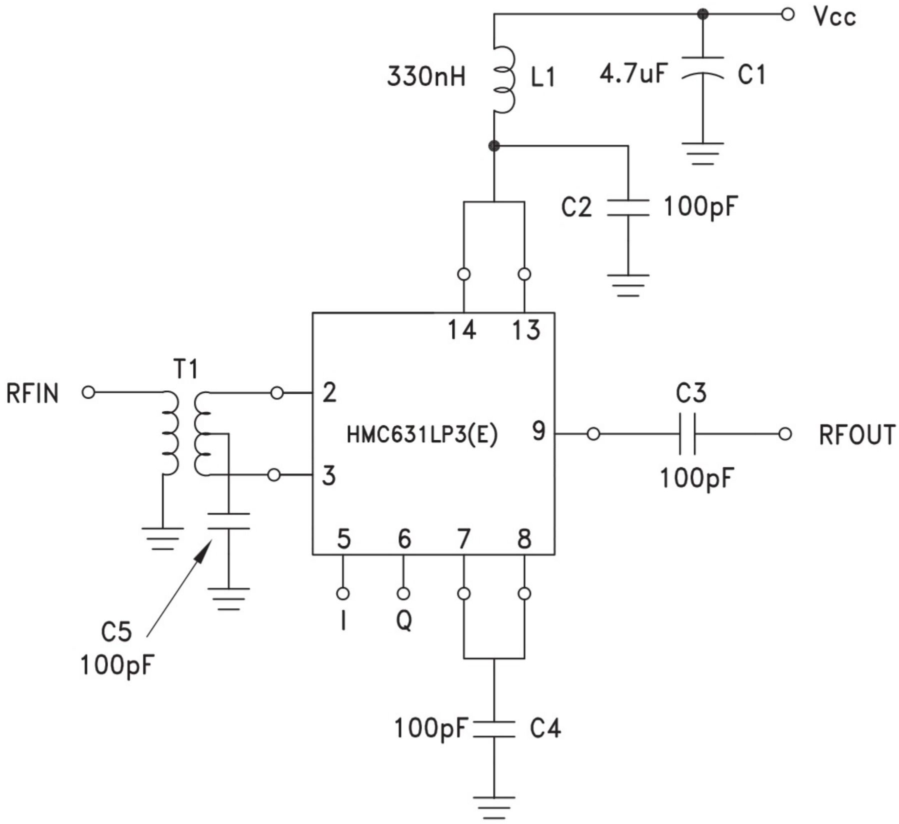

Figure 3.2: Evaluation board for HMC631;Analog Devices Hettite VM

3.2 Balun

A balanced-to-unbalanced transformer(balun) is a circuit used to transition from a balanced signal to an unbalanced signal and vice versa. The device has 3 ports. Two are balanced ports and one is unbalanced port. The signal applied at the unbalanced port of the balun is converted into two signals of equal amplitude and opposite polarity at the two balanced ports. The input power to the balun is split equally between the two balanced ports. Thus the output power will be 3dB less than the input power. The characteristic parameters of the balun are insertion loss, return loss, amplitude balance, phase balance etc.

3.3 Combiner

Power Combiner or Power Divider is a passive RF device which has 3 ports. For power combiner,the signal powers applied at two of the inputs are combined to give the output at the output port. When it is operated as power divider,the input given at the input port splits equally into each of the output ports. An example of a power combiner is the Wilkinson Power Combiner. The implementation diagram is given below:

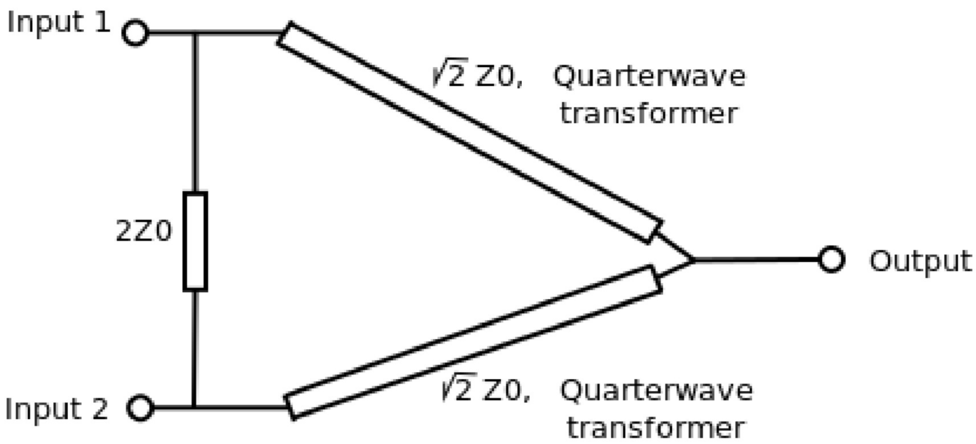

Figure 3.3: Power Combiner

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3.4 Power Detector

It is designed for RF power measurement and control applications for various high frequencies. The detector provides an accurate RMS representation of any broadband input signal. The output is a temperature compensated, monotonic representation of real signal power.

HMC1020LP4E(the one which is used in full duplex) is ideally suited to those wide bandwidth, wide dynamic range applications requiring repeatable measurement of real signal power, especially where RF/IF wave shape and/or crest factor change with time.

3.4.1 Evaluation Board for PD

Analog Devices provides an evaluation board to support this IC, HMC1020.It contains various passive components as we discussed for VM. The Application circuit is shown below

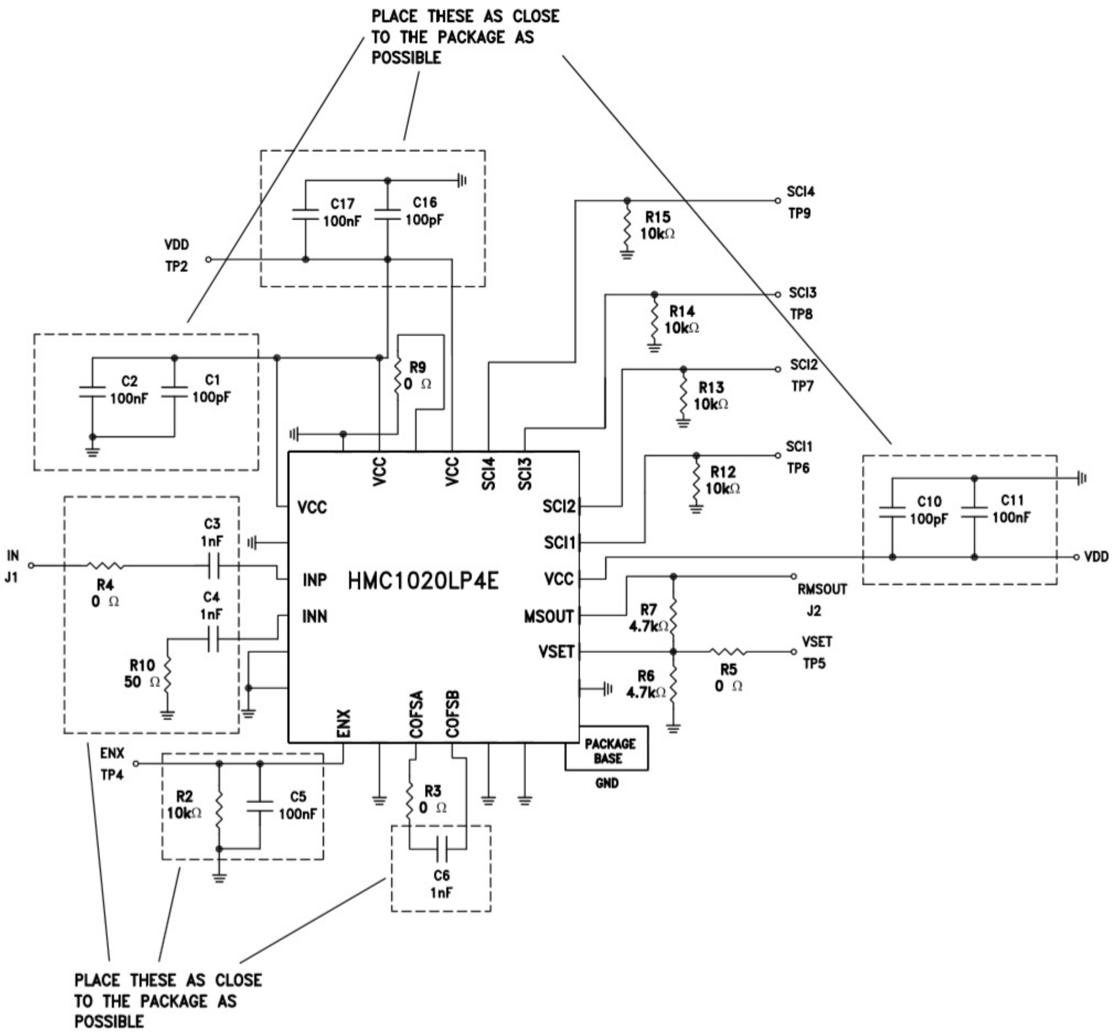


Figure 3.4: Evaluation Board for PD

3.5 Ladder Low Pass Filter

Ladder network filters are composed of alternate series and shunt reactive elements like inductors and capacitors as shown in figure 3.3.The signal flow is assumed from left to right. The source is the thevnin equivalent of the entire circuitry feeding the filter, and the load is the thevnin equivalent of the entire circuitry being fed by the filtered signal

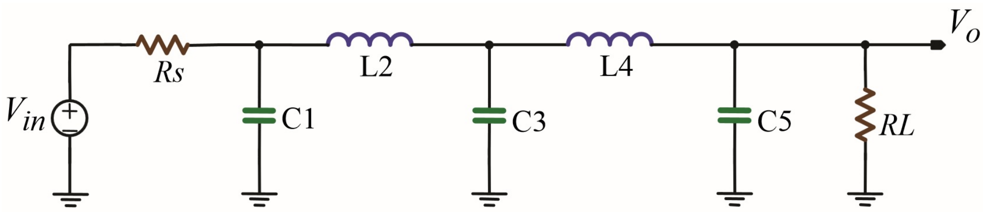
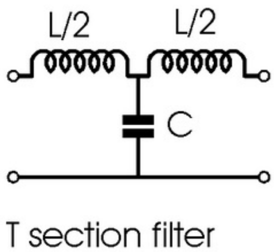


Figure 3.5: Ladder LPF



L = Zo / (pi x Fc) Henries

C = 1 / (Zo x pi x Fc) Farads

Fc = 1 / (pi x square root (L x C) Hz

Where
Zo = characteristic impedance in ohms
C = Capacitance in Farads
L = Inductance in Henries
Fc = Cutoff frequency in Hertz

Figure 3.6: Design Equations

Chapter 4

Implementation Details and Results

4.1 Design using KiCad and TINA

The entire board except DAC and Circulator were designed using KiCad and simulations were done with TINA(provided by TI).The first block I designed was the LPF with cutoff of 10kHz. Three of them are being used in the overall network.

4.1.1 Ladder LPF

The design was using the equation set defined in Fig:3.6. I designed a 6th order LPF. Since their are two unknowns(LC) and two equations(based on Zo and Fc), we don't need to fix any value. The filter thus simulated and its frequency response obtained using TINA is shown below:

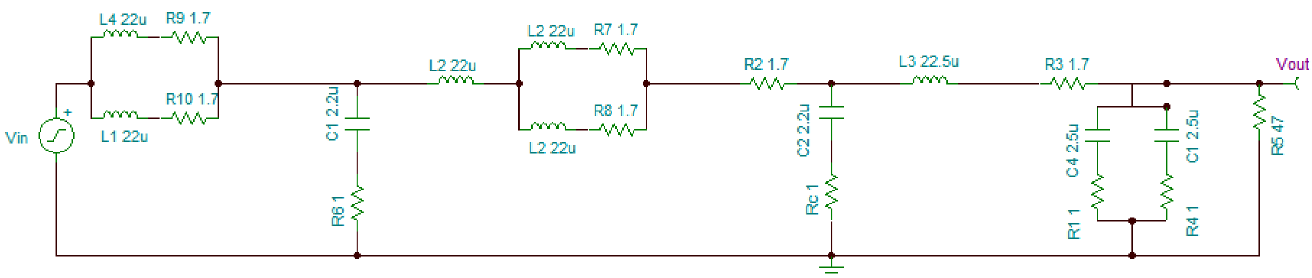


Figure 4.1: Ladder LPF

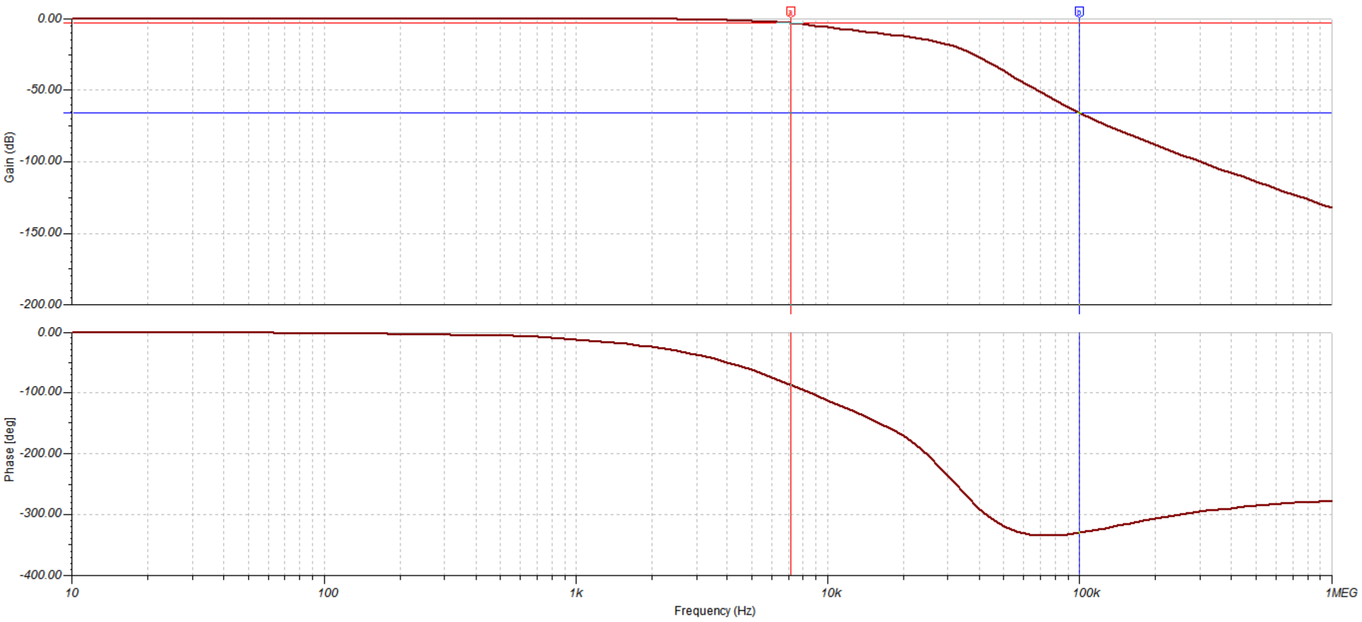


Figure 4.2: Filter Responses

4.1.2 Method applied for Baseband Cancellation:

In base-band cancellation, a sinusoidal signal is transmitted from one USRP and the amplitude and phase shifted version is transmitted from another USRP which is MIMO synchronized with the rst USRP. Now the amplitude of both signal are matched to the precision allowed and then phase is varied over the full range.It was found that when single tone is transmitted, this method works fine and cancellation close to noise oor was achieved(as seen on spectrum analyzer).But with the increase in number of tones, the cancellation was not uniform and random(not always same each time) over the tones.This may be due to various effects of group delay, narrow-band assumption which gives rise to non uniform cancellation over different frequency bands and also many other artifacts of harmonics, phase noise as explained above which makes the cancellation limited. The residual value was measured with viper board ADC and the RSSI chip available in IITM Full Duplex Board Rev 1 and the setup used is as shown below :

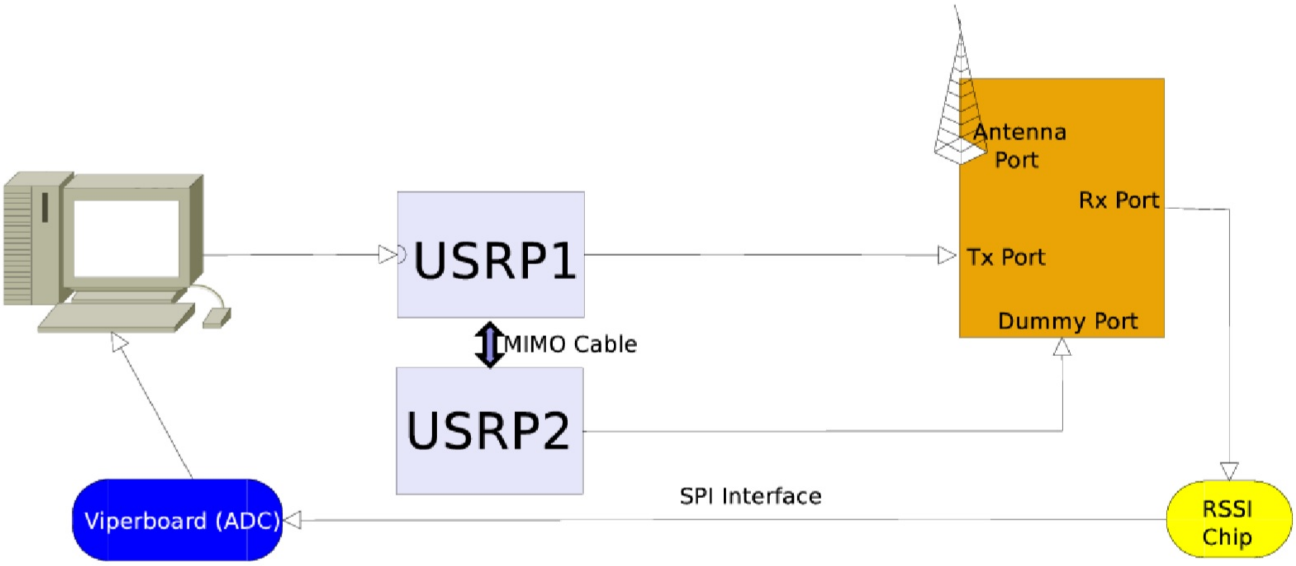


Figure 4.3: Base-band Cancellation

4.1.3 Method applied for RF cancellation

With the limited scope of cancellation in BB method as explained, for getting required amount of cancellation in analog domain it was decided to explore the analog cancellation with practical signals by generation dummy/cancellation signal in RF domain itself by tapping a small amount of transmitted signal itself.So here a copy of known transmitted signal was generated and then used to cancel the self interference signal at the receiver.

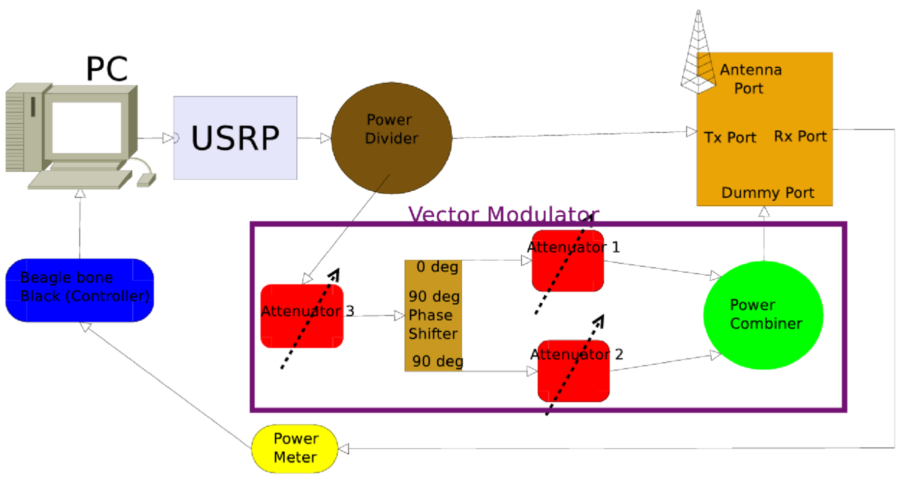


Figure 4.4: RF Cancellation

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The concept is simple and yet powerful enough to provide with around 60 dB of analog cancellation. Firstly , the transmitted signal is divided into two equal (can be unequal also to save power)parts and main part is connected directly to the transmitter . On the supplementary/dummy path we set the required attenuation and opposite phase as incurred by the signal from transmitter to receiver and pass it to dummy port which leads to cancellation of the self interference to very low levels .Here we have three different attenuators which combines to provide the signal a range of different attenuation and any phase change.This signal is adjusted at an amplitude value(found with the help of spectrum analyzer once and for all and then the search path amplitude is adjusted to be around that) equal to main path and opposite phase which ultimately combines to give very low signal.

Range of attenuation value that can be achieved are from 0 to 31 dB and correspondingly phase change of 8 to 91 can be achieved.Now to cancel the delay of the supplementary path is adjusted with respect to main path such that opposite phase occurs at the setting of 45 degrees.Also the cancellation prevails over a high bandwidth upto 5 MHz .

4.1.4 Evaluation Boards

The evaluation boards for VM, Power Combiner, PD and the LPF were combined so as to create a single board. Impedance matching was ensured(matched to 50 ohms). Track width needed was found out from PCB Calculator option provided in KiCad.

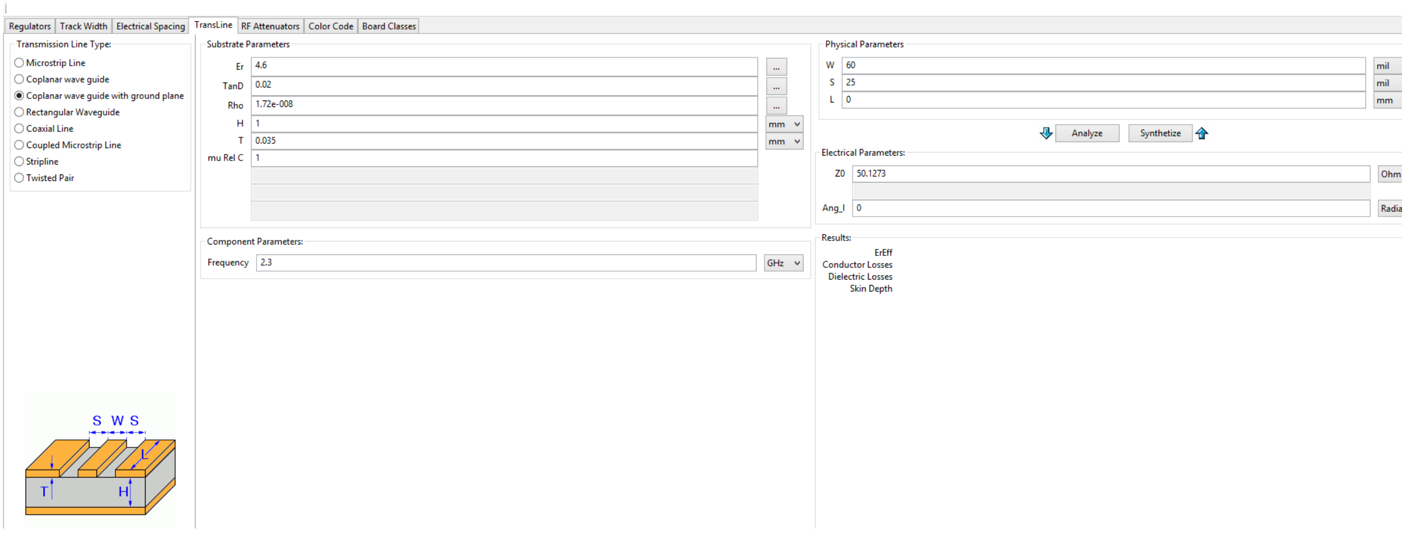

Figure 4.5: PCB Calculator

Once after the connections are made, a Design Rules Check was performed. In fact it is advisable to do frequent DRCs while making the component connections

4.1.5 Obtained Results and Observations

The entire board layout was made using KiCad. The IC packages that are used in the board are QFN16,QFN24,DFN8 and DFN16. All passive components were choosed based on the availability in Digikey(online supplier).And the board fabrication was done by MyRo PCB,China

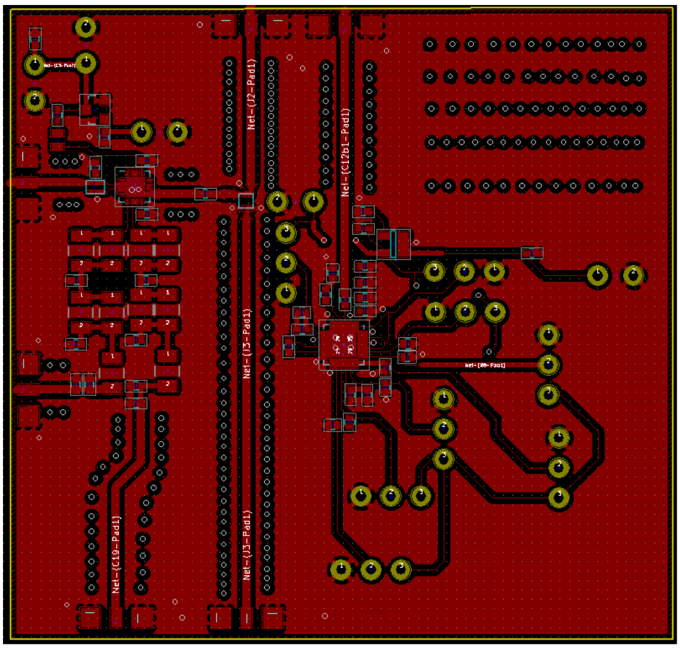

Figure 4.6: PCB front copper layer

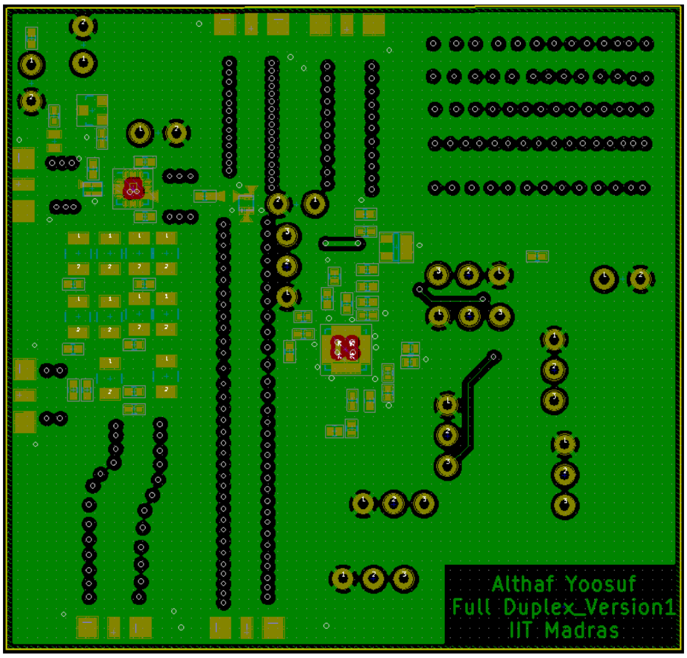

Figure 4.7: PCB back copper layer

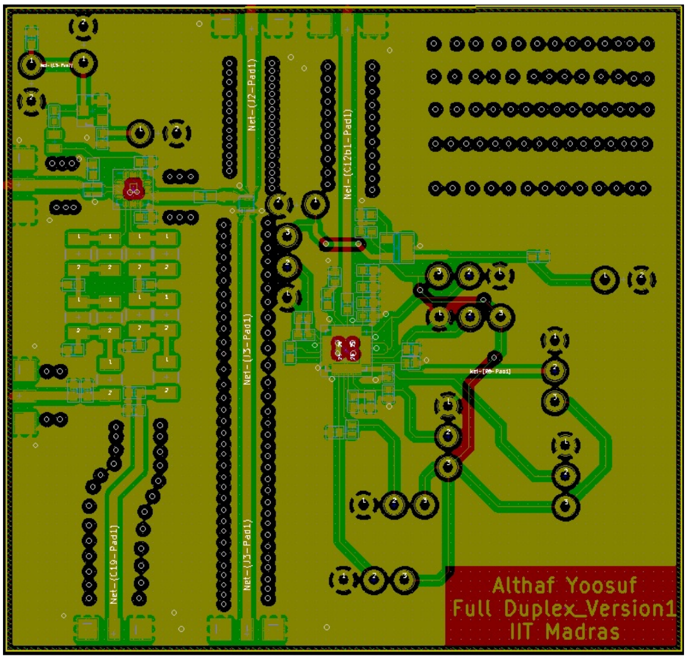

Figure 4.8: overall structure

Chapter 5

Conclusions and Future Work

Full Duplex communication can have major advantages over present communication but to achieve that self interference is a major hurdle.Here we achieved the analog self interference cancellation of around 60dB with the sine wave for the leakage component that is while there are no reflection path (antenna port terminated) and around 43 dB along with the reflections considered (with antenna installed) but this occurs primarily due to impedance mismatch between the antenna and the dummy port since the reflectors are present at large distance and will cause less reflected power.So a total of 60 dB is shown to be achievable through the setup used which certainly brings the desired received signal in the dynamic range of ADC so that it can be extracted through Digital baseband techniques.

In the board I designed, two blocks(DAC and Circulator) are not yet taken care due to time constraint.We plan to use a 24bit,16 channel DAC for this purpose with necessary supporting components.

LIST OF PAPERS BASED ON THESIS

1. Arjun Nadh, Joseph Samuel, Ankit Sharma, S. Aniruddhan, and R. K. Ganti
   A linearization technique for self-interference cancellation in full-duplex radios *IEEE Trans. on Wireless Communications(May 2016).*