RF Self-Interference Cancellation in Full Duplex Wireless Communication

A Project Report

submitted by

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CERTIFICATE

This is to certify that the thesis titled **RF Self-Interference Cancellation in Full Duplex Wireless Communication**, submitted by **Saumitra Padeer**, 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 my 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.

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Finally, I would like to thank my friends and family members for their unwavering support. This project wouldn't have been possible without their constant encouragement.

Abstract

In this thesis, an RF self-interference cancellation for in band full duplex wireless transceivers is implemented. Full duplex systems transmit and receive the signal at the same time and the same frequency. So, the biggest interference comes from the transmit signal of the node which is known as the self-interference. This self-interference power should be reduced below the noise floor so that the desired received signal can be detected effectively.

Self-interference can be cancelled in both analog and digital domain. In analog domain, there are baseband and RF cancellation techniques. RF cancellation prevents LNA from getting saturated, and analog cancellation prevents ADC from getting saturated.

In this thesis, two stage design has been implemented for the RF self-interference cancellation. A high resolution phase shifter has been designed for the vector modulator and the spectral shaper.

The Gradient Descent algorithm is used for optimizing the voltage variable phase shifter and the voltage variable attenuator so that best cancellation can be achieved.

Contents

List of Figures

List of Tables

Abbreviations

SI	Self-Interference
SIC	Self-Interference Cancellation
FDD	Frequency Division Duplex
OFDM	Orthogonal Frequency Division Multiplexing
ADC	Analog to Digital Converter
LNA	Low Noise Amplifier
RF	Radio Frequency
TX	Transmitter
RX	Receiver
MIMO	Multiple Inputs Multiple Outputs
PA	Power Amplifier

Chapter 1

Introduction

1.1 Introduction to In-Band Full Duplex

In today's world, we want to send more data with the minimum resources. In half duplex systems, which are generally used, antenna can transmit the data or receive the data but can do only one at a time. The disadvantage of half duplex is that, when one device is sending the data, then another has to wait, this causes the delay in sending the data at the right time. This problem can be solved with the full duplex.

Traditionally, full duplex denotes transmitting and receiving at the same time on different frequencies, which is known as frequency division duplex (FDD) or out-of-band full duplex. In-band full duplex is a technique where the antenna can transmit and receive at the same time and at the same frequency, which theoretically doubles the throughput.

But the major problem with the in-band full duplex is the significant self-interference that is generated by the transmitter of the same node as that of the receiver. This interference signal cannot be suppressed by filters because it is within the desired band of the receiver.

1.2 Aim and Motivation

The transmit signal is usually very strong as compared to the receive signal. Now, as transmission and reception are done by the same antenna in full duplex, the transmitted (self-interference) signal completely overshadows the desired receive signal. Therefore, it becomes inevitable to cancel the self-interference signal in order to receive the desired signal.

For a system with antenna for both transmission and reception, the system knows the transmit signal. So, a circuitry can be built to subtract this transmit signal from the receive signal so that only the desired part of the receive signal goes to the receive chain. This prevents the saturation of the receive chain and thus completes the aim of full duplex, which is transmission and reception at the same time and at the same frequency.

The aim of this project is to obtain the maximum cancellation for the 3.5 GHz input signal over the bandwidth of 100 MHz. The peak power of the signal is 52.5dBm.

Chapter 2

Literature Survey

This chapter discusses the related works done in the area of full duplex. It sheds light on the various RF cancellation techniques implemented earlier. The second part of the chapter discusses the design of high resolution phase shifter.

2.1 RF Cancellation Techniques

2.1.1 Antenna Cancellation Technique

Antenna separation is one simple way of getting the isolation between the transmitter and the receiver when dedicated antennas are used for transmission and reception. However, impractically large separation would be required between the TX and RX antennas to get the enough reduction to make full duplex possible with only antenna separation. So, to get more SI cancellation, Choi et al. proposed an additional technique called antenna cancellation [1]. In this technique, two antennas are used for transmission and one is used for the reception. Transmit antennas are put at distance d and d+λ/2 away from the receive antenna. So, the transmit signals from both the antennas interfere destructively at the receive antenna location and creates a null.

This technique has three major limitations. The first is that it requires three antennas. Three antenna MIMO system can theoretically triple the throughput, whereas full duplex can only double the throughput. Also, null regions of destructive interference can be created in the far field due to two transmit antennas. Second is that the cancellation suffers for the wideband signals. Finally, the third limitation is that it requires manual tuning of the second transit antenna, which is impractical in a real scenario.

2.1.2 Balun Cancellation Technique

To get the SI cancellation, we can invert the known transmitted signal and then add it to the self-interference signal. For signal inversion, Mayank et al. used a simple design based on a balanced/unbalanced (Balun) transformer [2]. This is a two antenna technique where the transmit antenna transmits the positive signal. At the receive antenna, the radio combines the negative signal coming from the balun with its received signal after adjusting the delay and attenuation of the negative signal to match the self-interference. Balun cancellation gives better results as compared to the antenna cancellation because balun inverts the complete signal. This ensures better cancellation across the band.

The limitation of this technique is that the balun may have engineering imperfections, such as leakage or a non-flat frequency response.

2.1.3 Spectral Shaper Based RF SI Canceller

Conventional SI cancellation techniques deal with phase-based RF cancellation, which results in non-flat spectrum. So, any second stage to improve the cancellation further would not be effective because of this non-flat residual RF spectrum. Ramasamy et al. [4] proposes a novel "Spectral Shaper" which is used in the second stage to make the spectrum of the second stage similar to the spectrum of the residual RF signal of the first stage. This second stage gives the significant improvement in the SI cancellation.

2.2 High Resolution Phase Shifter

A continuous voltage controlled phase shifter can be made using the varactor diode. Garver proposed a design of phase shifter in which a varactor diode is put on one terminal of the circulator [6]. Power in the first port of the circulator is reflected by the diode on the second port and emerges from the third port with a phase and amplitude dictated by the reflection coefficient of the diode. When the reverse voltage applied to the varactor diode is varied, the phase of the reflection coefficient changes while its magnitude remains high. This requires very less power and responds quickly to the changes in the reverse voltage. This phase shifter gives 360° phase shift linearly with the voltage and also has the constant insertion loss.

Chapter 3

Self-Interference Cancellation

This chapter focuses on the technique used for the SI cancellation. The cancellation technique used in this project is based on the work done by Ramasamy et al. [4]. A single stage cancellation circuit is explained in the first part of the chapter. Later, a two stage cancellation circuitry is built to get the maximum cancellation and spectral shaper is used to improve the cancellation from the second stage.

3.1 Mathematical Model

We need to build a mathematical model of the single stage cancellation system to understand the spectral profile of the RF residual self-interference signal. Using this spectral profile, the spectrum of the second stage will be decided so that the maximum cancellation can be achieved. The model of the single stage SI cancellation system is shown in Figure 3.1.

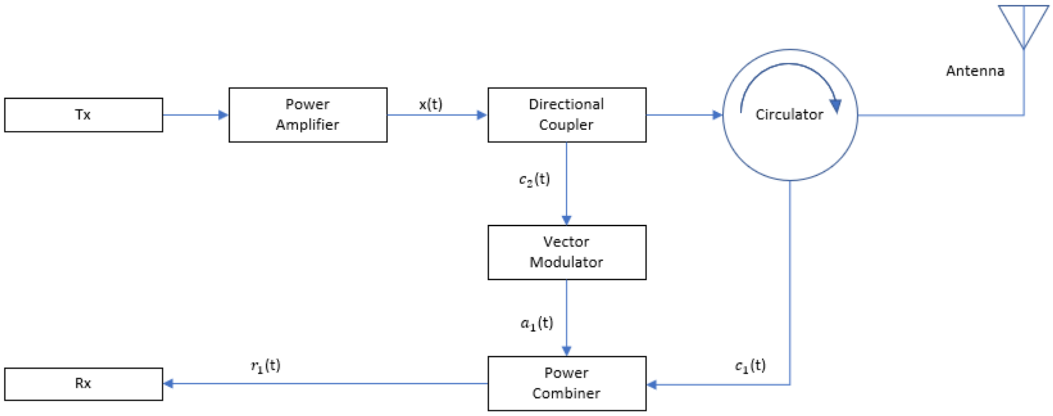


Figure 3.1: Typical RF SI cancellation System for Full Duplex Radios

Here, 'Tx' block represents the RF upconverted signal which is being fed to the 'Power Amplifier' block. The output of PA is,

$$x(t) = m(t)sin(2\pi f_c t) \tag{1}$$

where, m(t) denotes the modulated signal in the analog domain and f_c denotes the carrier center frequency.

The signal denoted by equation (1) is fed to the circulator through the coupler. It then gets transmitted to the antenna. The leakage of the circulator is the largest self-interference. It will be expressed as

$$\begin{aligned} c_1(t) &= L_1 m(t - \tau_{g1}) sin(2\pi f_c(t - \tau_{p1})) \\ &= L_1 m(t - \tau_{g1}) sin(2\pi f_c(t - \frac{\phi_a}{2\pi f_a})) \end{aligned} \tag{2}$$

where, L_1 denotes the circulator loss, τ_{g1} denotes the group delay in the circulator leakage path, τ_{p1} denotes the phase delay in the circulator leakage path, ϕ_a denotes the phase shift experienced by the f_a frequency component, $\forall\ (f_c - \frac{BW}{2}) \leq f_a \leq (f_c + \frac{BW}{2})$.

We have to cancel the SI signal represented in the equation (2). The part of Tx signal taken through the coupling port of the coupler will be used to cancel the SI signal. The Tx coupled signal is represented by,

$$c_2(t) = L_2 m(t) sin(2\pi f_c(t - \tau_{p2})) \quad (3)$$

where, L_2 is the coupling factor of the coupler and τ_{p2} is the phase delay experienced by the Tx coupled signal. Group delay is not shown here and will be taken into account later.

The signal denoted by the equation (3) is fed to the Vector Modulator. The Vector Modulator is tuned such that the signals a_1 and c_1 will have the same amplitude and their phases will be 180° apart. The output of the Vector Modulator is expressed as

$$a_1(t) = A_{VM} L_2 m(t - \tau_{g2}) sin(2\pi f_c(t - \tau_{p2}) + \phi_{VM}) \quad (4)$$

where, A_{VM} denotes the tuned value of the amplitude of the Vector Modulator (optimally, $A_{VM} = \frac{L_1}{L_2}$), ϕ_{VM} denotes the tuned value of the phase of the Vector Modulator (optimally, $\phi_{VM} = 2\pi f_c(\tau_{p2} - \frac{\phi_a \pm \pi}{2\pi f_a})$) and τ_{g2} denotes the net group delay experienced by the output of the Vector Modulator.

After putting the optimum values of A_{VM} and ϕ_{VM}, equation (4) becomes

$$a_1(t) = L_1 m(t - \tau_{g2}) sin(2\pi f_c(t - \frac{\phi_a \pm \pi}{2\pi f_a})) \quad (5)$$

Now, a_1 will be added to the Rx path using the power combiner. This will significantly cancel the SI signal coming from the circulator leakage. So, the RF residual SI signal will be

$$r_1(t) = \frac{1}{\sqrt{2}}(a_1(t) + c_1(t)) \tag{6}$$

where, $\frac{1}{\sqrt{2}}$ arises due to the 3dB power combiner loss.

So, the RF self-interference cancellation (SIC) will be

$$SIC_1 = c_1(t) - r_1(t)$$

Therefore,

$$SIC_1 = 10log_{10}(\frac{\int_{f_c-\frac{BW}{2}}^{f_c+\frac{BW}{2}} \mid \int_{-\infty}^{\infty} c_1(t)e^{-j2\pi ft}dt \mid^2 df}{\int_{f_c-\frac{BW}{2}}^{f_c+\frac{BW}{2}} \mid \int_{-\infty}^{\infty} r_1(t)e^{-j2\pi ft}dt \mid^2 df}) \tag{7}$$

From equation (7), we can see that the SIC after single stage depends on the spectrum of $r_1(t)$. And clearly, the spectrum of the signal $r_1(t)$ will not be flat as the vector modulator will be tuned only for the center frequency. Hence, the spectrum will be of notch shape where center frequency will experience the maximum cancellation and corner frequencies will experience less cancellation.

3.2 Implementation of Second Stage

Figure 3.2 shows the two stage implementation of the SI cancellation system. Another vector modulator is used in the second stage to improve the cancellation further. The tuning of this vector modulator will be done separately after the first vector modulator. This way, it can be checked easily that how much extra cancellation the second stage is giving.

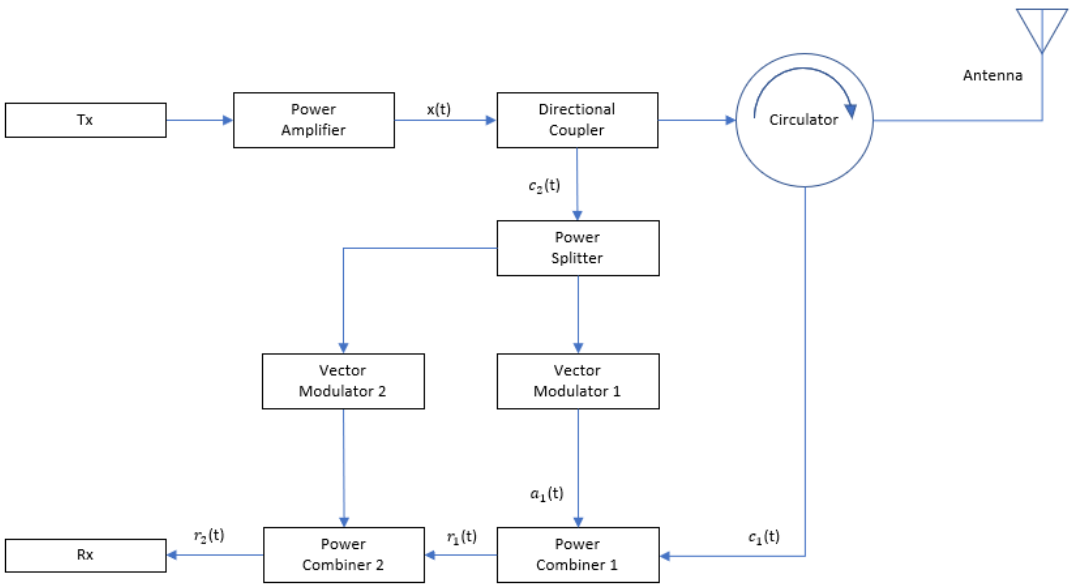


Figure 3.2: Two Stage RF SI cancellation System for Full Duplex Radios

As it is shown in the previous section, the first stage SIC distorts the spectral response of the residual SI. But here, the second stage we are using will have a flat response. So, there will be an amplitude imbalance between them. This will cause the second stage to make no significant improvement in the SIC.

To further improve the SIC, we need to make the spectrum of the second stage similar to that of the first stage residual signal $r_1(t)$. Then amplitude and phase of this signal will be adjusted using the second vector modulator so that it can maximize the total cancellation.

A novel "Spectral Shaper" design is introduced by Ramasamy et al. [4] to shape the spectrum of the second stage according to our need.

3.3 Spectral Shaper

The spectral shaper consists of two blocks, viz. variable attenuator and variable phase shifter. The two blocks are connected in each path as shown in the Figure 3.3.

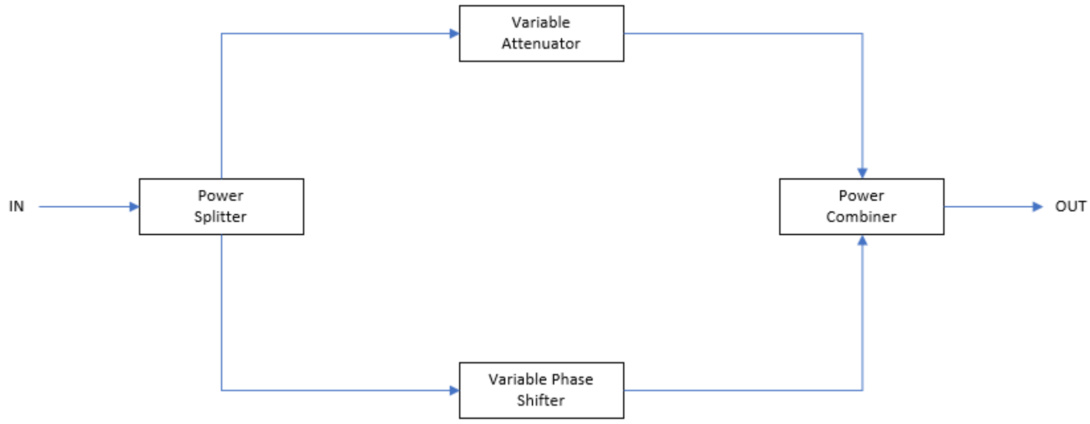
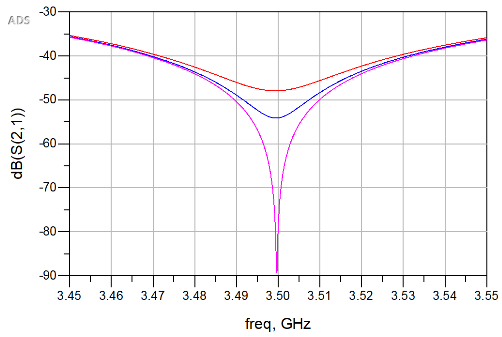


Figure 3.3: Spectral Shaper

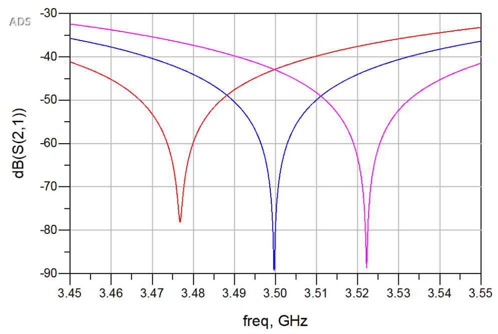
These two paths are combined using the power combiner. As these two paths will have nearly the same power and the phase shifter introduces 180° phase shift in the second path, we will get a notch at the output.

The variable attenuator decides the slope of the notch, whereas the variable phase shifter decides the frequency at which the notch occurs. The position and the slope of the notch should exactly match the first stage residual signal $r_1(t)$ to get the maximum cancellation.

Figure 3.4 shows the performance of the spectral shaper with variable attenuation and phase.



(a) Variable attenuation and fixed phase



(b) Variable phase and fixed attenuation

Figure 3.4: Spectral Shaper Performance

Figure 3.4a shows the changes in slope at notch location as we use three different values of attenuation. Figure 3.4b shows the changes in notch location as we use three different values of phase shift.

Therefore, by tuning the attenuator and the phase shifter, we can mimic the shape of first stage residual signal $r_1(t)$, which can significantly suppress the signal $r_1(t)$ and thereby increase the overall cancellation.

3.4 Implementation of Second Stage with Spectral Shaper

Figure 3.5 shows the block diagram for spectral shaper based two stage RF SI cancellation system for full duplex radios. The spectral shaper is connected in the second stage as we have discussed earlier. The amplifier is connected in the second stage to increase the dynamic range.

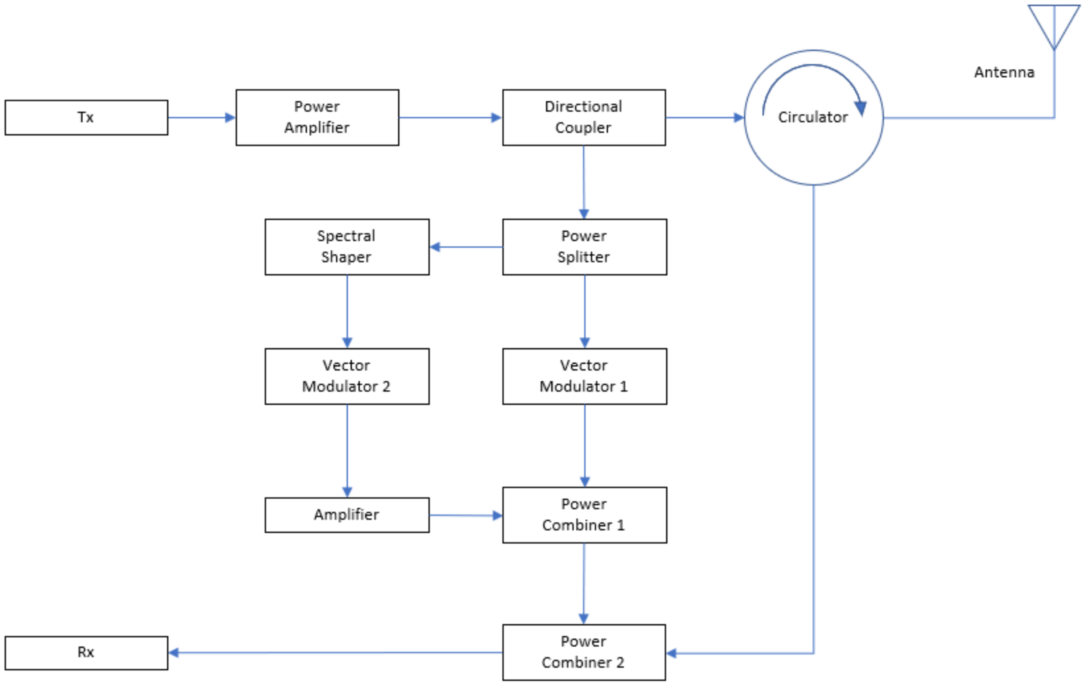


Figure 3.5: Spectral Shaper Based Two Stage RF SI cancellation System

As we can see, the first and the second stages are combined using the power combiner first and then their combination is combined with the SI signal coming from the circulator leakage. This is done to avoid an extra power combiner loss in the reception path.

Chapter 4

Phase Shifter

This chapter discusses the design of high resolution variable phase shifter. The design discussed in this thesis is inspired by the work done by Garver [6] which uses the reflection property of the diode connected to the circulator.

The phase shifter should have the following three properties:

- phase shift should vary linearly with the voltage
- the insertion loss should be constant
- phase shift over the voltage range should be 360°

The advantages of this varactor based phase shifter over the digital phase shifters are: no digital-to-analog converter is required; only four diodes are required, making the device smaller and less expensive to fabricate; and the diodes are operated at reverse bias which makes the device faster and more efficient.

4.1 Theory

In this thesis, a 3dB hybrid coupler is used to build the phase shifter instead of a circulator. The advantage of using a coupler circulator is that the power returning to the input port due to reflections at other ports is almost zero. This is because the output port is completely isolated from the input port, and the other two ports, where varactors are connected, cancel each other's powers going towards the input port. Whereas in the case of circulator, any reflections occurring at the output port will directly go towards the input port.

As we can see in Figure 4.2, four diodes are connected to the coupler (two at each port, excluding input and output ports). A change in the reverse bias voltage changes the capacitance of the varactors and thereby changes the phase of the reflection coefficient. We want the amplitude of the reflection coefficient to be close to one so that the S_{21} of the phase shifter is minimum.

Each varactor has a parallel varactor connected to it through the $\lambda/4$ transmission line. This introduces a 90° phase lag to the other path. This is done to double the phase shift over the voltage range of the varactor.

Figure 4.1 shows the pin configuration of the 3dB hybrid coupler used in the design of the phase shifter.

Pin 1	Pin 2	Pin 3	Pin 4
Input	Isolated	-3dB $\angle\theta - 90$	-3dB $\angle\theta$
Isolated	Input	-3dB $\angle\theta$	-3dB $\angle\theta - 90$
-3dB $\angle\theta - 90$	-3dB $\angle\theta$	Input	Isolated
-3dB $\angle\theta$	-3dB $\angle\theta - 90$	Isolated	Input

Figure 4.1: Coupler Pin Configuration (Image Credit: X4C35J1-03G Datasheet)

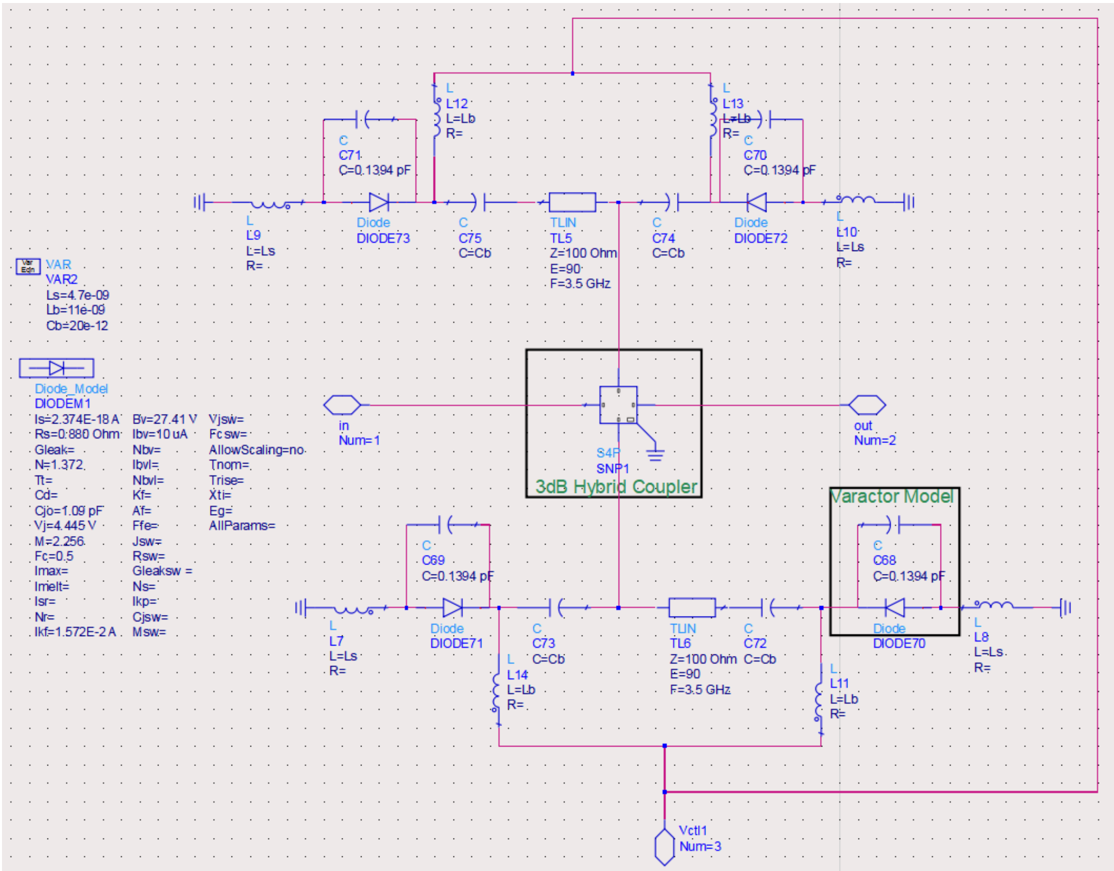
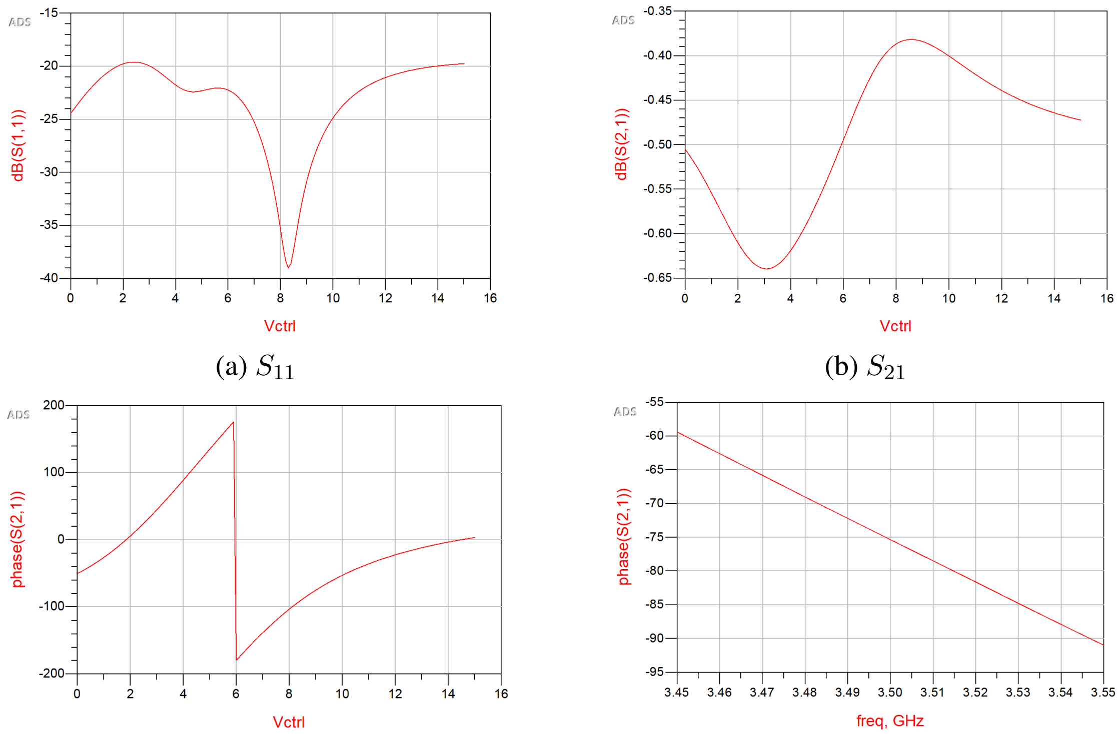


Figure 4.2: Phase Shifter Schematic

4.2 Schematic Simulation Results

The phase shifter is simulated in Keysight ADS schematic tool. The values of inductors and capacitors are fixed such that the phase shifter gives 360° phase shift over the voltage range, keeping the value of S_{11} minimum. Also, we want P_{1dB} of the phase shifter to be high. And, phase shift across the bandwidth should be very low to get the maximum cancellation.



(a) S_{11} (b) S_{21}

(c) Phase Shift vs Control Voltage (d) Phase Shift vs Frequency (Worst Case)

Figure 4.3: S-Parameters of Phase Shifter Schematic

Figure 4.3 shows the S-Parameters of the phase shifter. In Figure 4.3d, maximum phase shift across the bandwidth of 100 MHz is shown. To find the worst case, voltage is varied in the steps of 1 V and phase shift is calculated at each voltage.

Figure 4.4 shows the worst case P_{1dB} of the phase shifter. To determine the worst case P_{1dB}, frequency is varied from 3.45GHz to 3.55GHz and voltage is varied from 0 V to 12 V. Then P_{1dB} is calculated at each value of the frequency and the voltage. In Figure 4.4, marker m2 indicates P_{1dB} of phase shifter schematic.

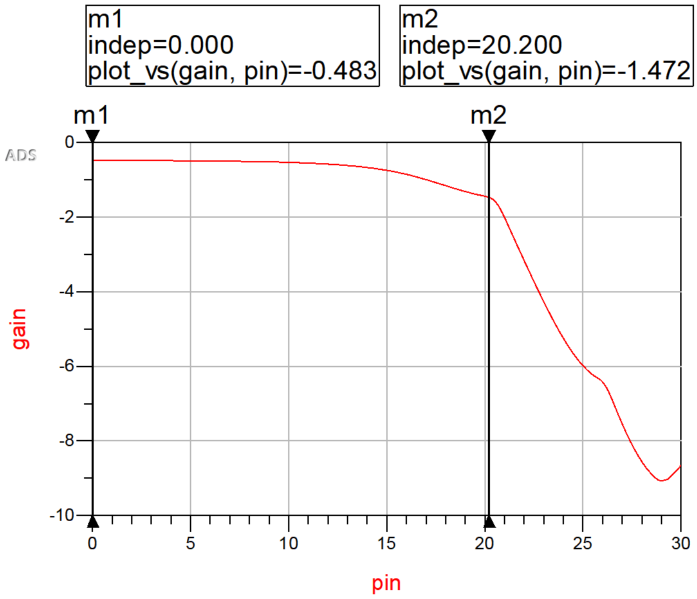


Figure 4.4: Phase Shifter Schematic P_{1dB} (Worst Case)

4.3 Layout Simulation Results

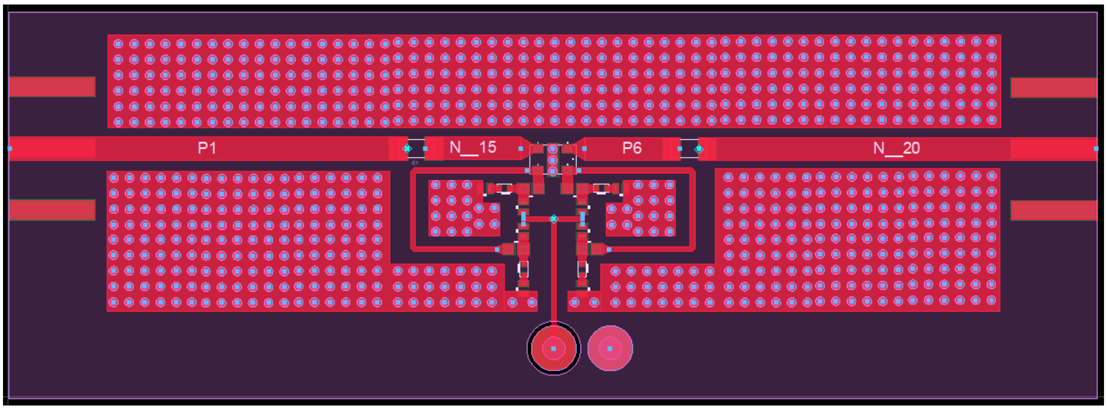
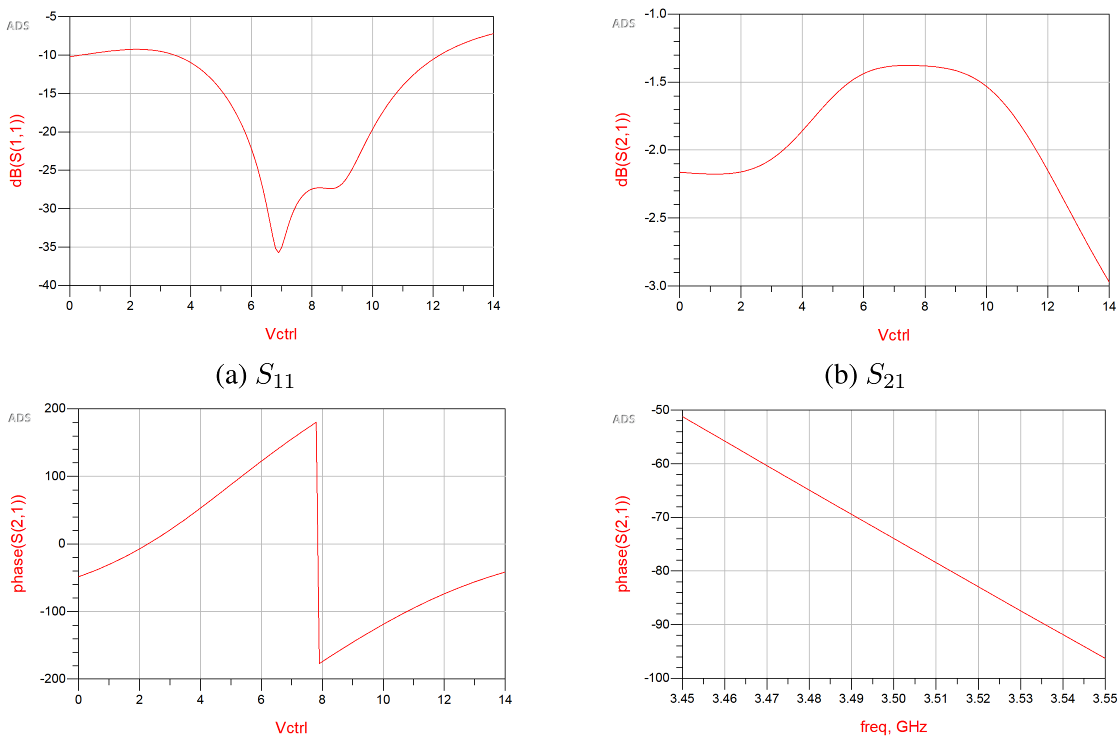


Figure 4.5: Phase Shifter Layout (Dimensions: 49 mm x 17 mm)

The symbol of the layout of the phase shifter shown in Figure 4.5 is created, and the components are connected to calculate the S parameters and the P_{1dB}. The components' values are the same as shown in the schematic simulation part (Figure 4.2).



(a) S_{11} (b) S_{21}

(c) Phase Shift vs Control Voltage (d) Phase Shift vs Frequency (Worst Case)

Figure 4.6: S-Parameters of Phase Shifter Layout

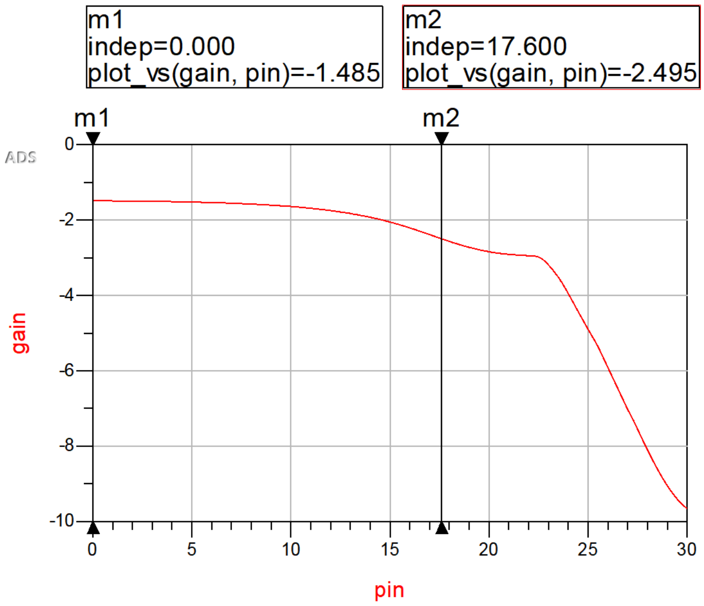


Figure 4.7: Phase Shifter Layout P_{1dB} (Worst Case)

In Figure 4.7, marker m2 indicates P_{1dB} of phase shifter layout.

The major differences between the schematic and the layout are in S_{11}, S_{21} and phase shift across the frequency band. S_{11} will be taken care of by the isolator. But larger phase shift across the bandwidth will surely affect the cancellation.

Chapter 5

Proposed Cancellation System

In this chapter, we will discuss the complete block diagram of the system used for the RF self-interference cancellation.

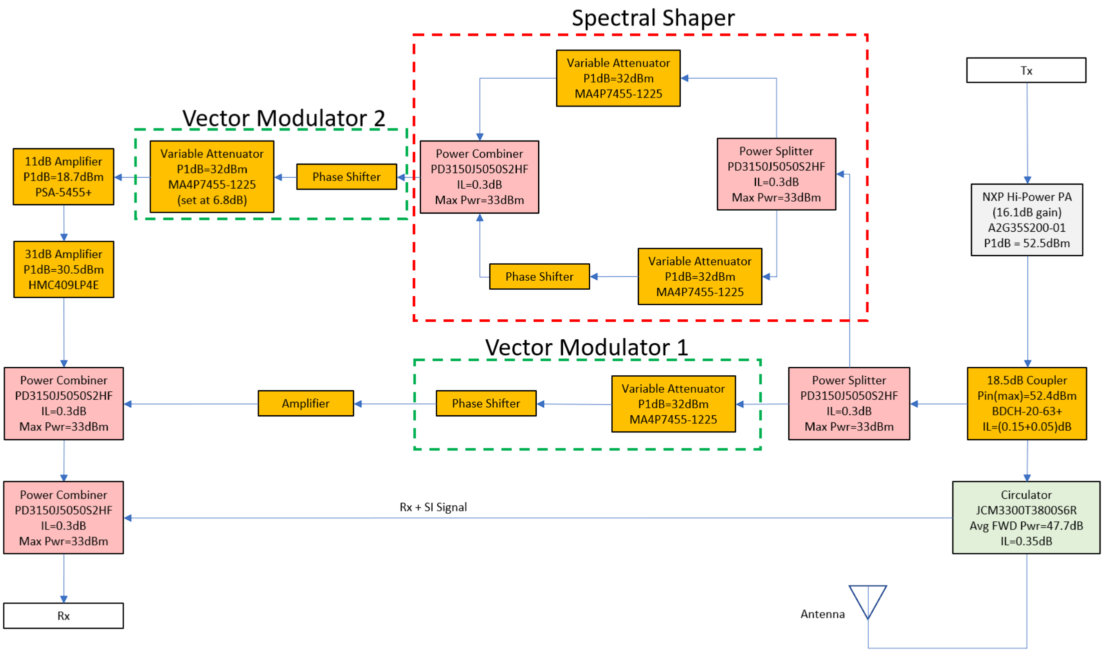


Figure 5.1: Setup for RF Self-Interference Cancellation

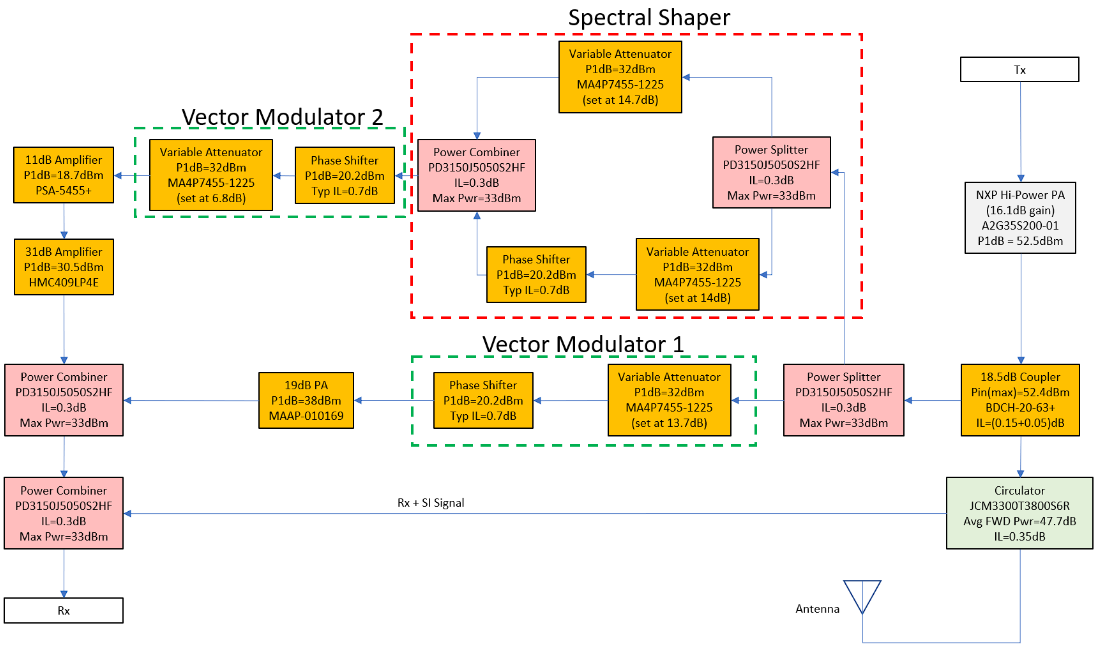


Figure 5.2: Block Diagram using Phase Shifter Schematic

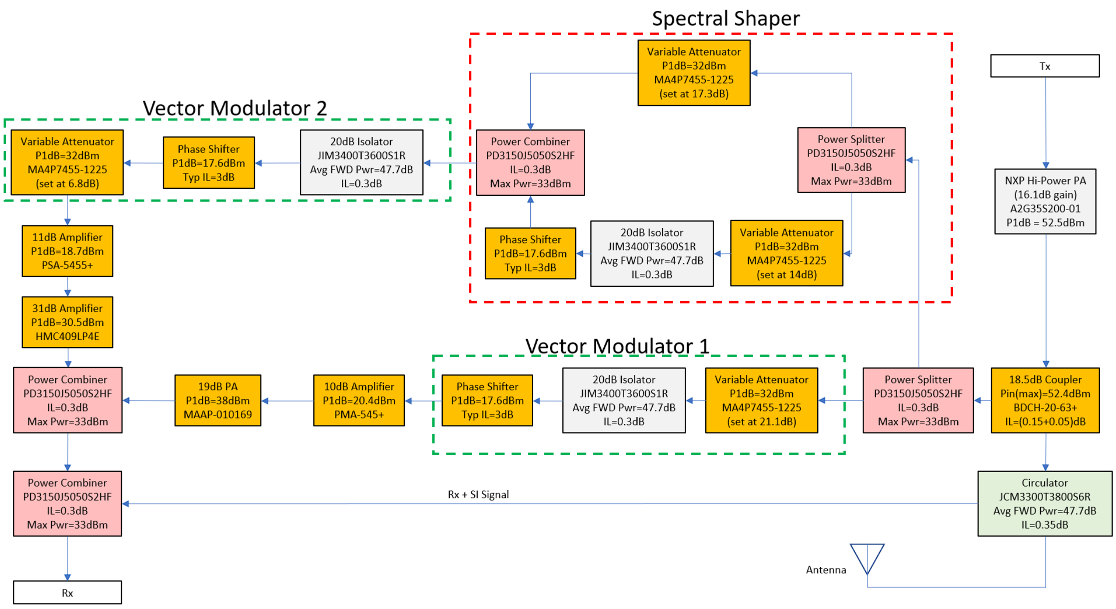


Figure 5.3: Block Diagram using Phase Shifter Layout

Figure 5.1 depicts every block used in the RF SI canceler setup. This setup resembles the basic block diagram of the cancellation system proposed in the Figure 3.5.

As we can see from the Figure 4.6a, phase shifter layout has poor S_{11} and that's why, an isolator is used before the phase shifter in Figure 5.3 to block the reflections from travelling back.

To cancel the SI signal, we have to make sure that our cancellation signal, which is coming from the coupler leakage, has the same amplitude as that of the SI signal, which is coming from the circulator leakage. So, in Figure 5.2, an amplifier is used in the first stage in series with Vector Modulator 1 to match power levels of the SI signal. Figure 4.6b shows that the loss of phase shifter layout is greater than that of the schematic. So, an extra amplifier is used in the first stage of Figure 5.3 to compensate this loss.

In the first stage, the vector modulator consists of a voltage variable phase shifter and a voltage variable attenuator. Phase shifter adjusts the phase and attenuator adjusts the amplitude. So, the combination of the attenuator and the amplifier makes sure that the amplitude is matched with the SI signal. On the other hand, the phase shifter makes sure that the cancellation signal is 180° out of phase with respect to the SI signal.

In the second stage, spectral shaper, vector modulator and two amplifiers are connected. As a single amplifier satisfying all the requirements was not found, we had to use two amplifiers. These amplifiers and the vector modulator play the same role in the second stage as they play in the first stage.

As discussed in the section 3.3, spectral shaper gives the notch shape to the spectrum. But in doing that, it reduces the power of the signal to a very low value. So, high value of amplification is required in the second stage to maintain the dynamic range using variable attenuator. Also, a variable attenuator is used as a fixed attenuation block before the phase shifter in the spectral shaper. It allows the variable attenuator in the upper path of the spectral shaper to use its maximum range.

Chapter 6

Tuning and Optimization of Variables

The tuning of variables is done by divide and conquer strategy. The first stage variables are tuned first, then the spectral shaper is tuned and lastly, the second stage variables are tuned.

For tuning the first stage variables, the second stage is disconnected from the circuit and the open terminals are connected to 50 Ω resistance. It is shown in the Figure 7.1. Manual tuning is done first to get the notch at the center frequency. Then optimization is applied to get the optimum value of phase and attenuation in the first stage to achieve the maximum cancellation. The gradient descent algorithm is used for the optimization.

After the first stage, the spectral shaper is tuned to achieve the notch at the center frequency and to make sure the slope of the notch at the center frequency is the same as that of the first stage residual signal. No optimization is required for the spectral shaper, as we only need to mimic the shape of the first stage residual signal.

Now, keeping the first stage variables constant, the second stage variables are tuned to get the better cancellation numbers than the single stage system. Then, the gradient descent algorithm is used to optimize the second stage variable to improve the cancellation further.

The tuning and the optimization of the system is done on the Keysight ADS schematic tool.

Chapter 7

Simulations and Results

For simulations, Keysight ADS schematic tool is used. An OFDM signal with center frequency 3.5 GHz and bandwidth 100 MHz is used as an input. The input has average power of 41.5dBm and PAPR of 11dB.

To make the simulation results more practical, S parameter files of amplifiers and attenuator are used. Also, the S parameter file of the coupler is used.

Attenuator shown in the simulation is not voltage controlled, as there are different S parameter files for different control voltages. So, for the simulation purpose, S parameter file of the attenuator for a particular voltage is chosen, and it is connected with an ideal phase shifter whose phase is being varied. This implementation is valid because the phase shift of the variable attenuator across the frequency band is similar for all the control voltages. The S parameter file chosen for the attenuator gives constant 6.8dB of attenuation.

Note: In_dBm and Out_dBm denotes the power at V_coup_in and V_rx respectively.

7.1 Simulations with Phase Shifter Schematic

7.1.1 First Stage Simulation

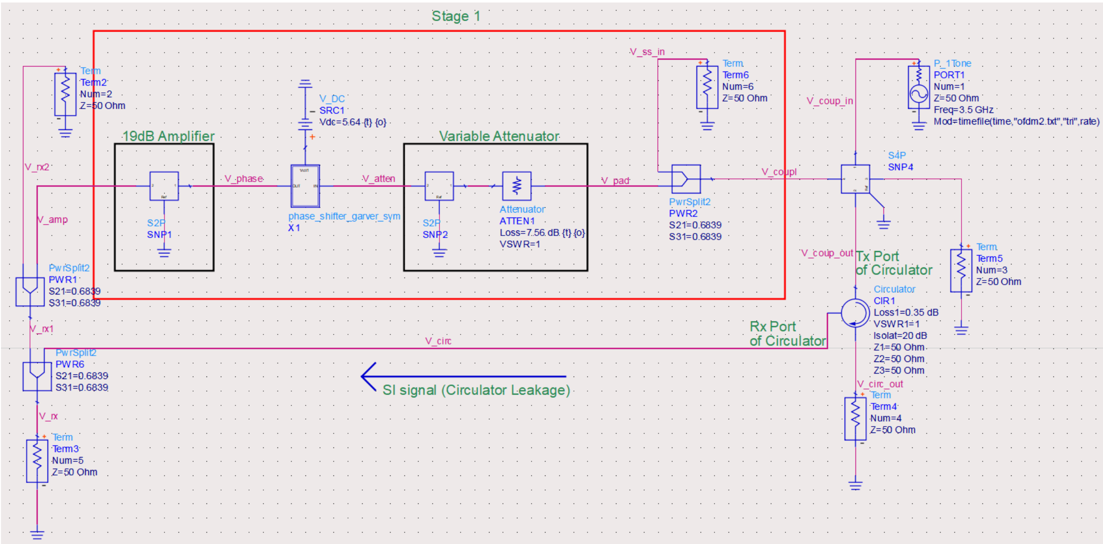
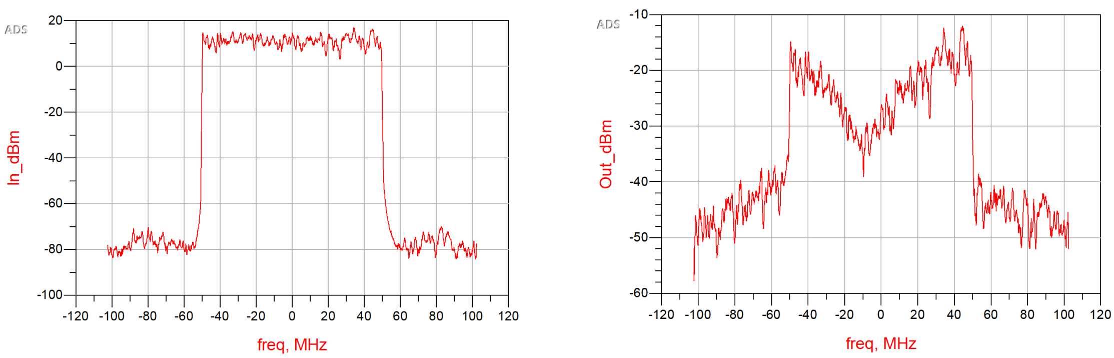


Figure 7.1: First Stage with Phase Shifter Schematic



(a) Input Signal (b) Residual SI Signal After Stage 1

Figure 7.2: Cancellation for First Stage with Phase Shifter Schematic

Tx Port of Circulator	Rx Port of Circulator	Residual SI Signal	Cancellation
41.5dBm	21.7dBm	9.3dBm	12.4dB

Table 7.1: Channel Power and Cancellation (First Stage with Phase Shifter Schematic)

7.1.2 Two-Stage System Simulation

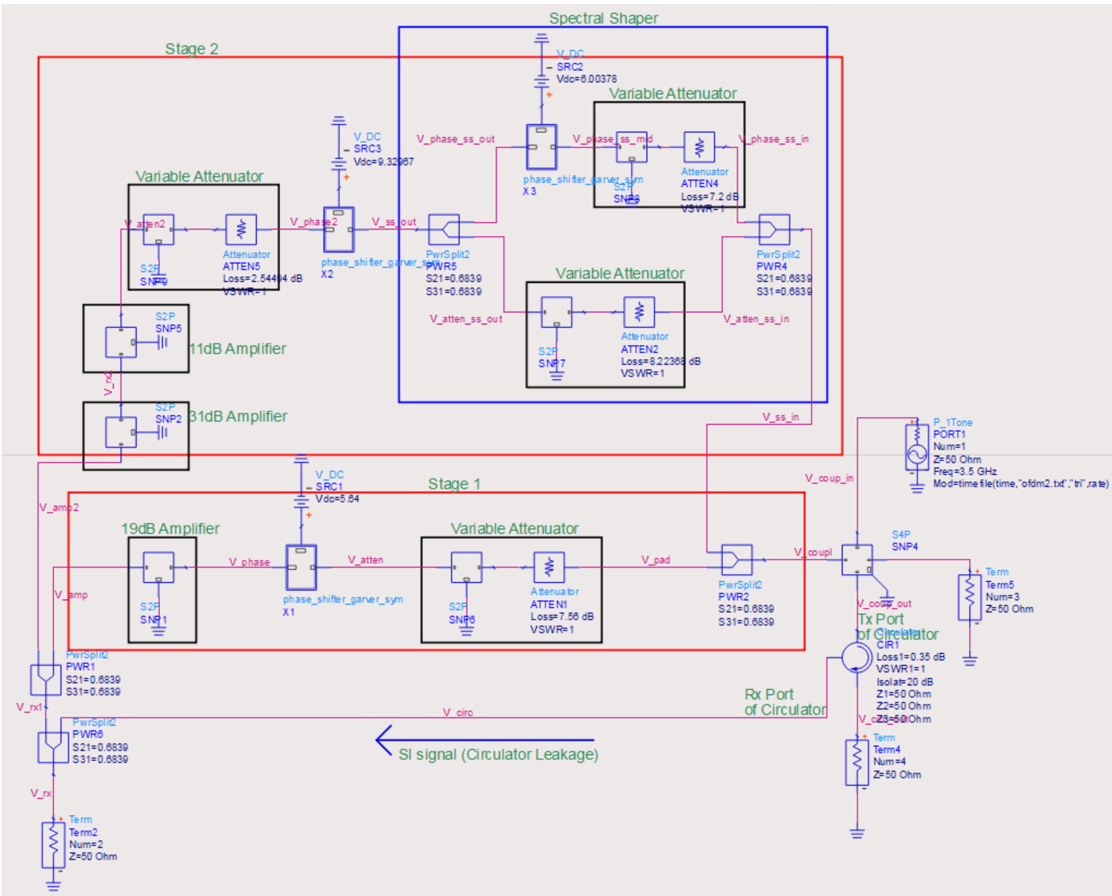
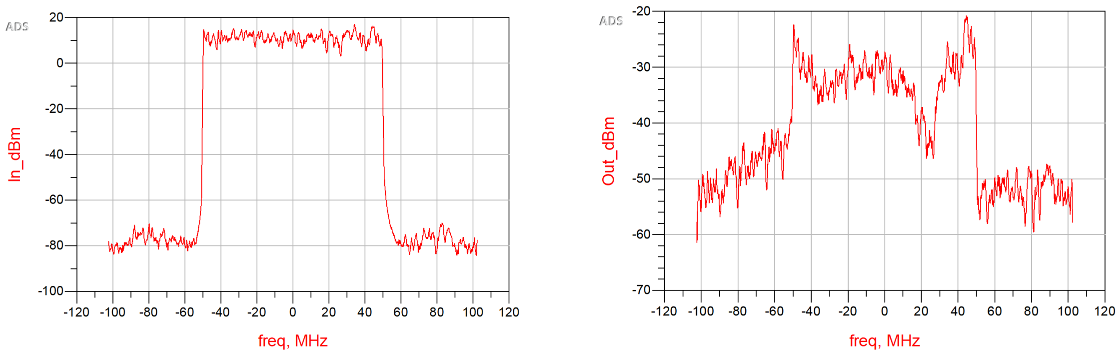


Figure 7.3: Two-Stage System with Phase Shifter Schematic



(a) Input Signal (b) Residual SI Signal After Stage 2

Figure 7.4: Cancellation for Two Stages with Phase Shifter Schematic

Tx Port of Circulator	Rx Port of Circulator	Residual SI Signal	Cancellation
41.5dBm	21.7dBm	0dBm	21.7dB

Table 7.2: Channel Power and Cancellation (Both Stages with Phase Shifter Schematic)

Circulator Isolation	Stage 1 Cancellation	Stage 2 Cancellation	Net Cancellation
19.8dB	12.4dB	9.3dB	41.5dB

Table 7.3: Total RF Self-Interference Cancellation with Phase Shifter Schematic

7.2 Simulations with Phase Shifter Layout

7.2.1 First Stage Simulation

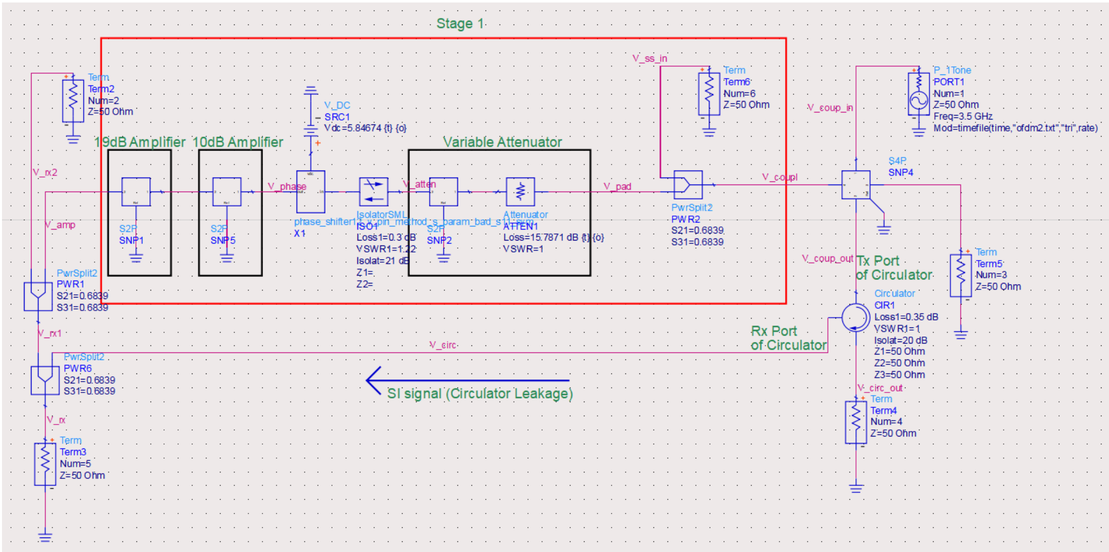
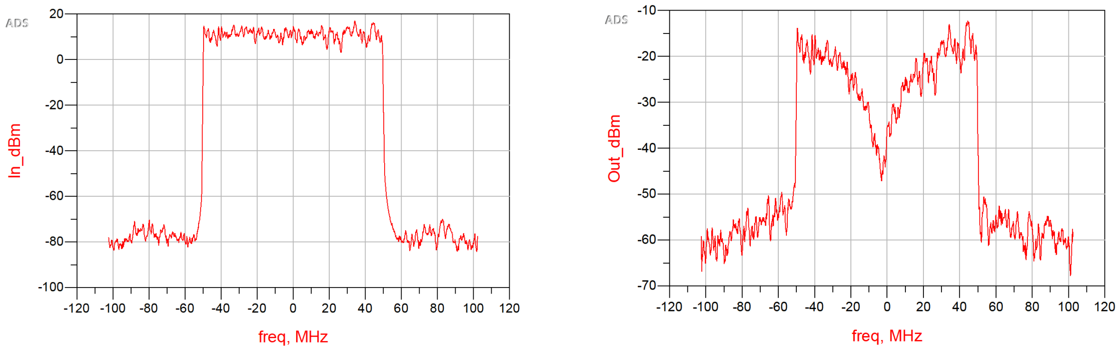


Figure 7.5: First Stage with Phase Shifter Layout



(a) Input Signal

(b) Residual SI Signal After Stage 1

Figure 7.6: Cancellation for First Stage with Phase Shifter Layout

Tx Port of Circulator	Rx Port of Circulator	Residual SI Signal	Cancellation
41.5dBm	21.7dBm	9.4dBm	12.3dB

Table 7.4: Channel Power and Cancellation (First Stage with Phase Shifter Layout)

7.2.2 Two-Stage System Simulation

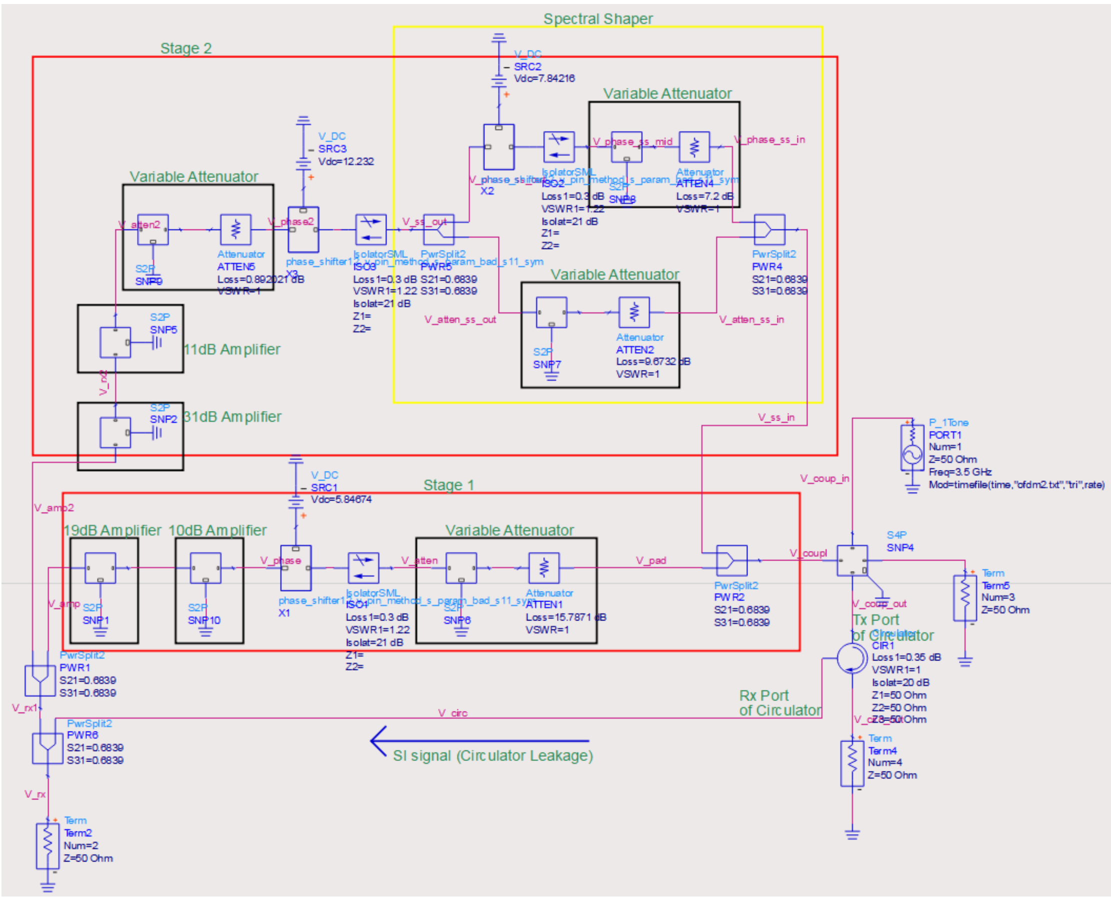
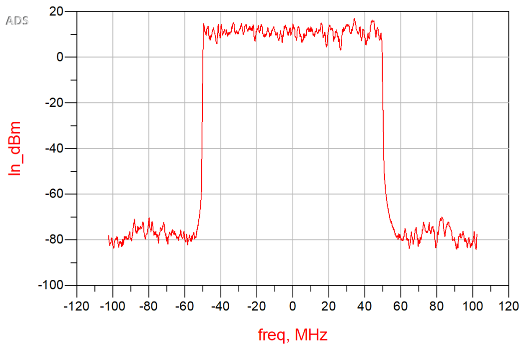
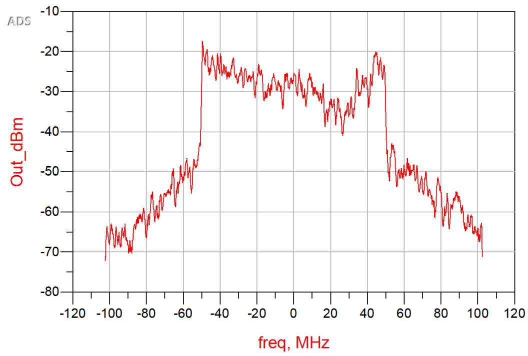


Figure 7.7: Two-Stage System with Phase Shifter Layout



(a) Input Signal



(b) Residual SI Signal After Stage 2

Figure 7.8: Cancellation for Two Stages with Phase Shifter Layout

Tx Port of Circulator	Rx Port of Circulator	Residual SI Signal	Cancellation
41.5dBm	21.7dBm	3.5dBm	18.2dB

Table 7.5: Channel Power and Cancellation (Both Stages with Phase Shifter Layout)

Circulator Isolation	Stage 1 Cancellation	Stage 2 Cancellation	Net Cancellation
19.8dB	12.3dB	5.9dB	38dB

Table 7.6: Total RF Self-Interference Cancellation with Phase Shifter Layout

7.3 Comparison between Phase Shifter Schematic and Layout Results

	with Phase Shifter Schematic	with Phase Shifter Layout
Circulator Isolation	19.8dB	19.8dB
Stage 1 Cancellation	12.4dB	12.3dB
Stage 2 Cancellation	9.3dB	5.9dB
Net RF Cancellation	41.5dB	38dB

Table 7.7: Total RF Self-Interference Cancellation Comparison

As it can be seen from Table 7.7, cancellation is reduced by 3.5dB in case of phase shifter layout. This result is expected as various non-linearities are taken into consideration while doing simulations with the layout.

Also, the major reduction in cancellation is happened in the second stage. This might be because two phase shifters are present in the second stage. So, they will give more phase shift across the band in layout as compared to the schematic.

Chapter 8

Conclusion and Future Scope

This thesis implemented a two-stage spectral shaper based RF self-interference cancellation technique. While using the phase shifter schematic, a cancellation of 12.4dB is achieved from the first stage and 9.3dB is achieved from the second stage. This, in addition with 19.8dB of circulator isolation, provides the total cancellation of 41.5dB for a 100 MHz OFDM signal. For phase shifter layout, a cancellation of 12.3dB is achieved from the first stage and 5.9dB is achieved from the second stage. This, in addition with 19.8dB of circulator isolation, provides the total cancellation of 38dB for a 100 MHz OFDM signal.

This technique can be expanded using more number of stages. But in that, the hardware would increase drastically, and the system will become complicated. Also, it can be observed that the cancellation achieved from the next stage will be less than the previous stage. So, it would be exciting to check how much cancellation can be achieved with the further stages, keeping the system fairly simple.

As we have seen, a high resolution phase shifter is very important to get the precise phase shift so that we can accommodate the smallest of phase variations. And, that's why, analog phase shifters are preferable in this case. But usually, the analog phase shifter has significant phase variations across the bandwidth, which makes it very difficult to get the phase inversion for the whole band. It ultimately hampers the cancellation.

While designing the analog phase shifter, it was noticed that as we try to get more phase range, the phase shift vs frequency also increases. So, to solve this, a digital phase shifter, with flat phase vs frequency response, can be used in series with the analog phase shifter. The analog phase shifter would only need the range equal to the resolution of the digital phase shifter. Then, the digital phase shifter will be used for the coarse tuning and the analog phase shifter will be used for the fine tuning. In my opinion, this should improve the cancellation numbers.

Bibliography

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Appendices

Appendix A

Board Stack-up

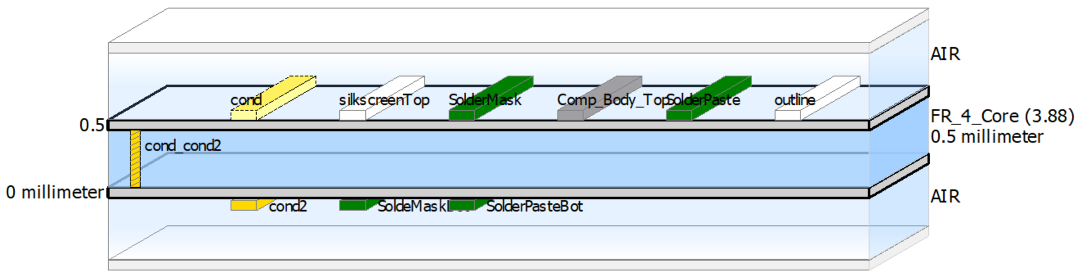

Figure A.1: PCB Stack-up

Substrate Material	FR4 (Isola 185HR)
TanD	0.023
Conductor Material	Copper
Conductivity	5.8e7
Conductor Thickness	35.56 um

Table A.1: Board Specifications

Appendix B

Attenuator Evaluation Board

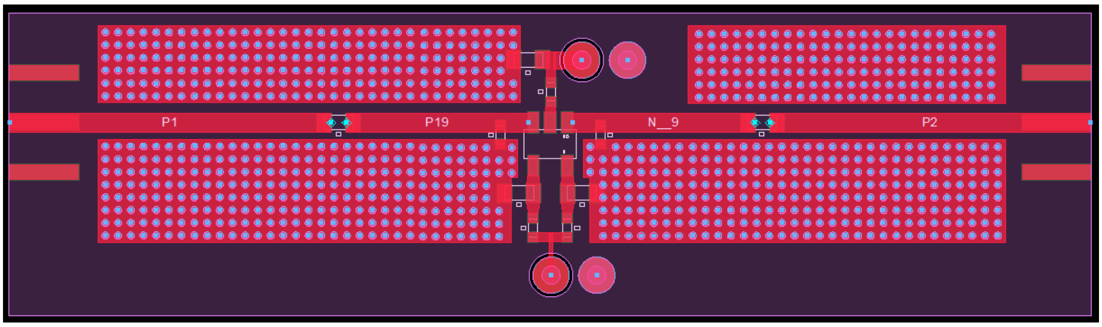

Figure B.1: Attenuator Evaluation Board Layout (Dimensions: 60 mm x 17 mm)

Appendix C

List of Components

Table C.1: Components

Sr. No.	Component Name	Component Number
1.	20dB Coupler	BDCH-20-63+
2.	Power Combiner/Splitter	ZB2PD-63+
3.	Variable Attenuator	MA4P7455-1225
4.	19dB Amplifier	MAAP-010169
5.	19dB Amplifier Eval Board	MAAP-010169-001SMB
6.	31dB Amplifier	HMC409LP4E
7.	31dB Amplifier Eval Board	108355-HMC409LP4
8.	Varactor	MA46H120
9.	3dB Coupler	X4C35J1-03G
10.	100 pF Capacitors	GCM1885C1H101FA16D
11.	1000 Ohms Resistors	ERJ-PA2D1001X
12.	20 pF Capacitors	CBR02C200F5GAC
13.	4.7 nH Inductors	LQW03AW4N7J00D

Sr. No.	**Component Name**	**Component Number**
14.	11 nH Inductors	LQW03AW11NJ00D
15.	11dB Amplifier	PSA-5455+
16.	11dB Amplifier Eval Board	TB-501+
17.	Edge SMA Connectors	EMPCB.SMAFSTJ.C.HT
18.	10dB Amplifier	PMA-545+
19.	10dB Amplifier Eval Board	TB-501+
20.	20dB Isolator	JIM3400T3600S1R