Intelligent Phase Shifter for mm-wave Beam Forming.

by

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ABSTRACT

Modern communication systems call for state-of-the-art links that offer almost idealistic performance. This requirement had pushed the technological world to pursue communication in frequency bands that were almost incomprehensible back when the first series of cordless cellphones were invented. These requirements have impacted everything from civilian requirements, space, medical diagnostics to defense technologies and have ushered in a new era of advancements.

This work presents a new and novel approach towards improving the conventional phased array systems. The Intelligent Phase Shifter (IPS) offers phase tracking and discrimination solutions that currently plague High-Frequency wireless systems. The proposed system is implemented on (CMOS) process node to better scalability and reduce the overall power dissipated. A tracking system can discern Radio Frequency (RF) Signals' phase characteristics using a double-balanced mixer. A locally generated reference signal is then matched to the phase of the incoming receiver using a fully modular yet continuous complete 360^{o} phase shifter that alters the phase of the local reference and matches the phase with that of an incoming RF reference. The tracking is generally two control voltages that carry In-phase and Quadrature-phase information. These control signals offer the capability of controlling similar devices when placed in an array and eliminating any ambiguity that might occur due to in-band interference.

DEDICATION

I humbly dedicate this effort to my sweet and loving

Mother and Father,
Whose affection, love, and encouragement made me achieve this success and honor,

Uncle
For the eternal love and support

Best friend Anyuta
For her constant and unwavering support

Along with my hard-working, dedicated, and well respected
Colleagues and Professors.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Modern Communication Systems

The world constantly pushes for top-notch performance, state-of-the-art connectivity that offers higher bandwidth, and excellent tracking capability. These requirements have made us move into the millimeter-wave (mm-wave) frequency regime. Operation at such high frequencies faces significant shortfalls in terms of degraded performance, expensive equipment.

The modern advances in integrated circuit technology offer performance and integration capability at a fraction of the required price in modifying existing technology and adapting mm-wave systems. One of the adequate solutions was to employ antennae arrays to transmit and reception these high-frequency signals [23].

The current trend of integrating phased arrays in portable devices has played a vital role in modern silicon development. These fully integrated systems overcome the drawbacks of developing, integrating discrete and large-scale platforms [23].

Multi-In-Multi-Out (MIMO) and multipath communication systems have become an increasingly common pursuit worldwide, especially in communication and wireless networking platforms [1]. MIMO is rapidly expanding due to better performance parameters and more extensive bandwidth requirements. These play a vital role in environments where clear line-of-sight (LOS) communication is very abstruse to achieve.

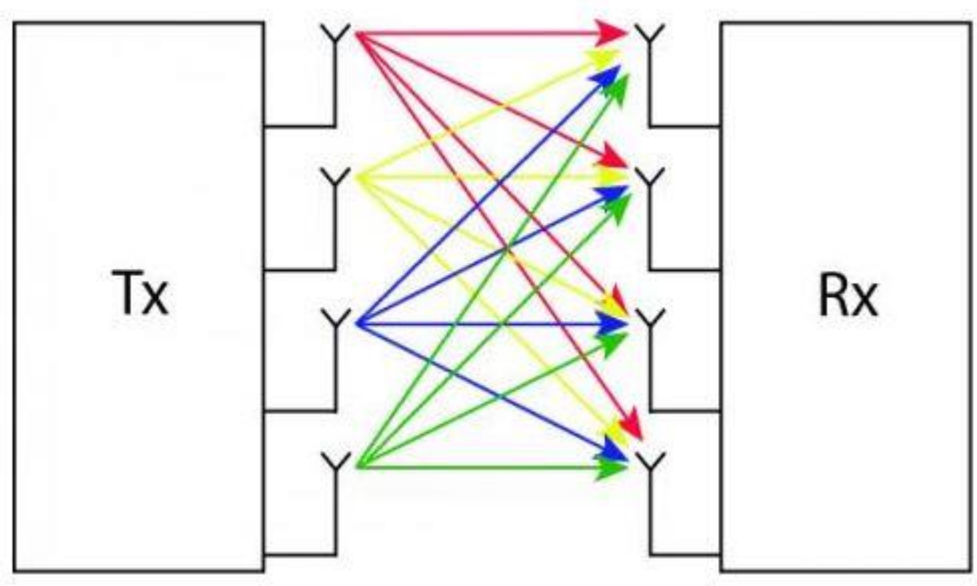

Figure 1-1 MIMO communication system.

A typical MIMO radio system sends data to the recipient over multiple signal paths simultaneously by using multiple transmit and receive antennas, improving signal strength and quality. MIMO splits data into streams that are then recombined at the receiver [1]. The receivers receive signals from multiple paths that often do not form LOS.

1.2 Beam Forming

A typical single transceiver antenna is based on the phenomenon of an isotropic antenna that radiates signals in all directions. The energy is distributed in all directions, but in some instances, especially the case of RADAR or focused wave communication systems, require the radio beam to be directed in a selected direction. Multiple Antennas placed in close proximity allow for generating the same signal at different instances in time. These overlapping waves interfere with each other. The interference is constructive in one direction (Making the signal stronger) and destructive in another (making the signal weaker). If executed correctly, this process can allow for the signal to be focused in a preferred direction.

Figure 1-2 Transmit antenna arrays demonstrated by keysight [21].

The fig. 1-2 represents a standard mm-wave transmit phased array demonstrated by keysight that offers beam directivity electrically [21].

1.3 Phased Array

The proliferation of systems that offer faster and better wireless communication systems calls for higher frequencies. Phased Array systems are devices that comprise multiple individual antennae arranged in a planar configuration separated by a fixed distance, generating a set of radio waves in a particular direction. By the concept of constructive interference, the energies directed in the same direction sum and increase the beam’s reach or signal transmitted. First demonstrated in 1905 by Karl Ferdinand Braun to aid the landing of aircraft during World War II. [2]

This requirement increases the ambiguity of the signal’s reception due to ionospheric conditions and solid objects that create a phase difference between the transmitted signal and the received signal. Modern systems reduce this ambiguity with the help of phased arrays that allow for better phase discrimination. The most common phased array receivers call for constant spacing between the antennae. Unconventional arrays where elements are placed at unequal distances or beyond Line of Sight (LOS) alter the architecture's complexity and increase phase determination. Fig. 1-3 represents the classical phased array.

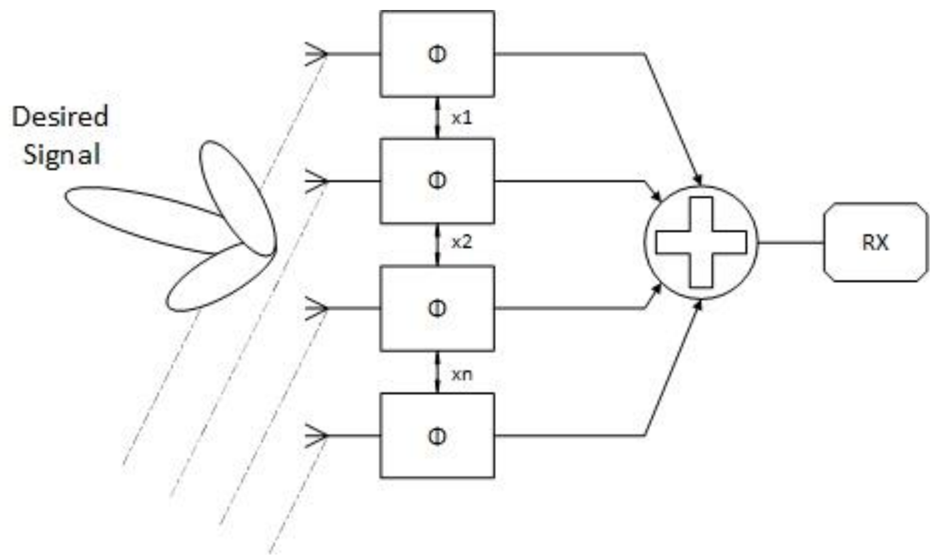

Figure 1-3 Phased array transceiver.

The principle of the phased array is to generate an electric field across an aperture. The antennas of a typical phased array system are placed almost half a wavelength apart. In other instances, sparse arrays where the transmit and receive modules are paced at distances farther than half a wavelength.

Arrays typically target adaptive beamforming. These techniques are incorporated to reduce interference or clutter in the receiver systems. In the presence of unknown interfering sources, the ability to discern the pure signal from interferers is convoluted. This ambiguity calls for better beamforming and interferer dampening techniques.

One of the common problems plaguing modern phased array communication systems is the phase mismatch, as regular phase shifter design formulae target capacity and signal amplitude but completely ignores phase mismatch due to the dependency on the elements. One standard solution is the use of more receiver modules [20] in cases where the phased arrays are spaced at distances far beyond the guidelines required for sparse arrays.

1.4 Outline of the Thesis

The thesis is organized in the following fashion: Chapter 2 introduces the concepts of phased array architectures, beamforming, and modern refinements transceiver modules. Chapter 3 discusses the system's overall architecture starting from the individual components to the entire fully integrated system. Chapter 4 provides detailed information on the circuit level implementation, the performance parameters, and system integration. Chapter 5 presents the simulation results of a completed intelligent phase shifter capable of matching the phase of a received reference to that of a locally generated signal. The thesis concludes in Chapter 6.

CHAPTER 2

BACKGROUND

2.1 Antenna Array

As the world enters the age where going cordless is necessary, this significant advancement comes with its own set of issues, from low data rates, limited bandwidth, lower gain. These enhancements call for a considerable overhaul of how a single bit of data is transmitted through a wireless medium. Thus dawned the age of the antenna array. The antenna array is a collection of antennas connected to work in tandem, forming one single antenna.

The individual antennas that form the array are referred to as elements. These elements are connected to a single RF module where each path leading to a component induces a necessary phase relation with the other elements. The radio waves radiated by each of these waves converge with each other. This convergence adds the radio signals in one direction through constructive interference enhancing the power that beamed in that direction. Simultaneously the signal undergoes destructive interference in the other direction, essentially removing any beam traces in that direction.

Figure 2-1 Nebo-M RADAR array [25].

Fig. 2-1 illustrates the most advanced (Radio Detection and Ranging) RADAR systems in the world, currently employed by the Russian military. The system utilizes 175 folded dipole antennas that radiate the beam in a vertical fan that can sweep on the horizontal axis.

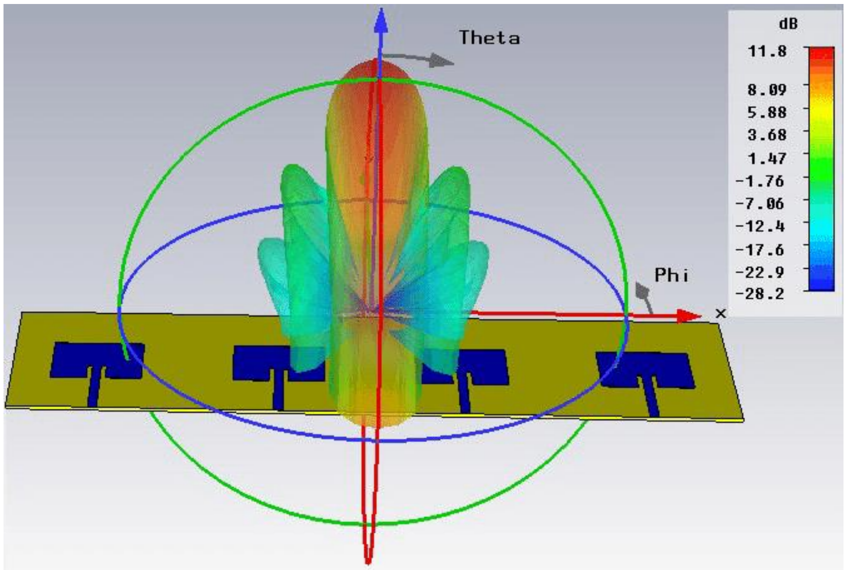

Figure 2-2 Antenna array radiation pattern [26].

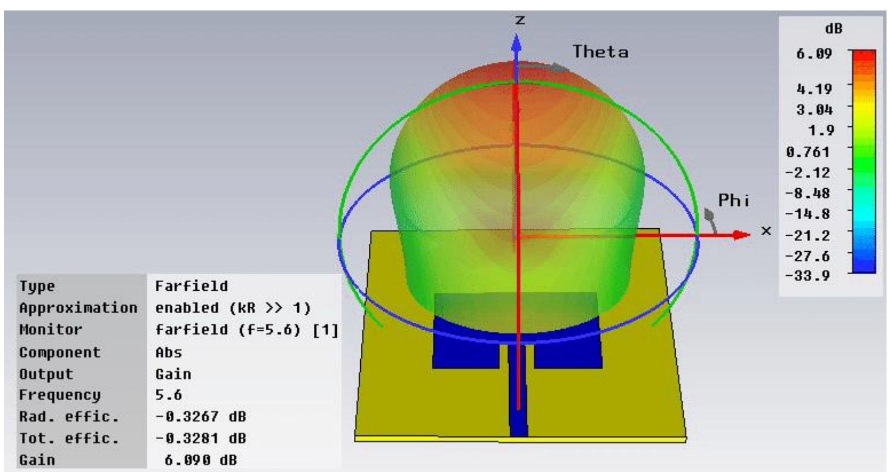

Figure 2-3 Antenna radiation pattern [26].

Fig. 2-2 and 2-3 represent the beam patterns of an array and a single element transmitter module. The beam's highlighted elements form the main lobe or the direction in which the antenna radiates maximum energy. When juxtaposed to that radiation pattern of the array, we observe that the radiated power in the case of the array is higher, and the size of the beam is relatively smaller, implying that the beam is more focused in one direction on the contrary to single element setup as represented in Fig. 2-3.

2.2 Advancement in modern arrays

Transmitter arrays have become a modern wireless standard, ranging from mobile communications to state-of-the-art detection systems that protect a country. This necessity has created a new realm of research that focuses on refining and advancing array systems, from developing intelligent antennas to novel algorithms that incorporate spatial signal processing for more advanced beam discrimination and detection.

One of the most prominent developments in modern array technology is the Active Electronically Scanned Array (AESA). This development introduced the concept of an analog transmit-receive phase modulation module, which can introduce controlled phase offsets in the RF signal. These phase offsets translate to changes in the direction of the antenna beam. AESA offers the ability to control the direction of the beam through the combination of control signals set at the circuit level. Each array module has its own exciter/receiver that eventually interferes constructively at the antenna level and offers the necessary beam steering.

The major driving factor for array development costs, generally modern phased arrays are expensive to implement and integrate. They were generally based on the application and the overall cost. Arrays are bifurcated into two types, Dense and sparse array architectures. Each is tailored to a particular audience and offers more significant advantages over the typical arrangements employed.

2.2.1 Dense Arrays.

Dense Array architectures are the arrangement of receive/transmit arrays, where the spacing between each element is fixed at a constant distance that is dictated by:

$$d = \lambda/2 \tag{2.1}$$

Where ‘d’ is constant over the entire frequency range for maximum available degrees of freedom. Dense arrays provide excellent integration so that modern mm-wave dense arrays can be integrated onto silicon dies, thereby making it one of the most effective communication modules. They are primarily designed to ease the circuit requirements at the RF-front end in beamforming applications and are based on the idea of oversampling data conversion systems.

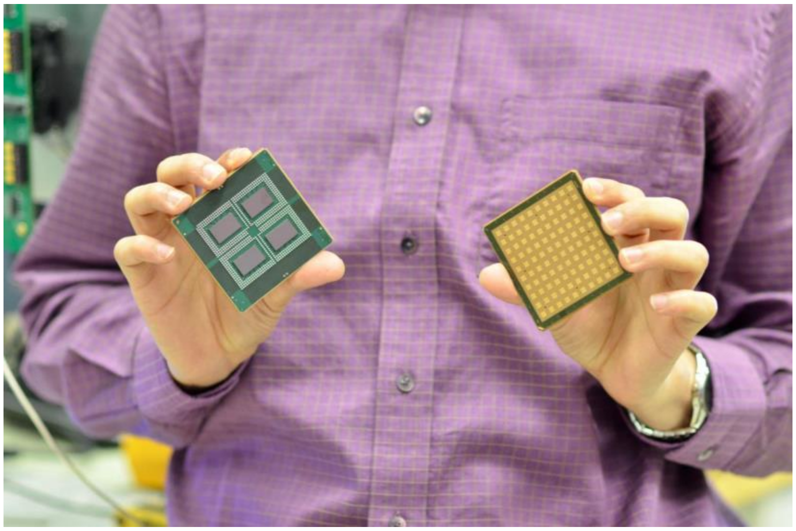

Figure 2-4 mm-wave antenna array by IBM for 5G [27].

Fig. 2-4 is a dense array that IBM developed to tackle the issues with beam reach and directivity. The entire array comprises 64 transmit and receive modules integrated into a package almost 7cm in length. Keeping in mind the exceptional advantages offered by the dense arrays, this architecture has its own set of drawbacks. Dense arrays are known to suffer from mutual coupling that exists between the antenna elements. The efficiency of the embedded antenna commonly characterizes Mutual coupling concerning the degradation of performance in multi-port systems [27]. Radiation pattern accuracy calls for better-developed front-end, phase shifters with greater resolution, power amplifiers that offer greater linearity become essential factors in developing dense arrays, thereby increasing the overall cost at the behest of precision, due to the shorter spacing that exists between the elements the bandwidth of the array is significantly reduces. At lower operating frequencies, the cost of implementation increases significantly, and integration is also cut short by the size of the radiating elements.

2.2.2 Sparse Arrays.

The limitations commonly known to plague the dense array arrangement were alleviated by developing a new architecture called sparse arrays. The sparse array is based on three implementation guidelines a) Many elements. b) Element spacing that is beyond the wavelength ($d > \lambda$). c) Quasi-random distribution of array elements.

Phased arrays that are often implemented with the elements placed in an equidistant grid-like arrangement with distances ranging over the wavelength produce grating lobes and blind spots due to mutual coupling. These issues are eliminated by removing the grided pattern and opting for almost random placement.

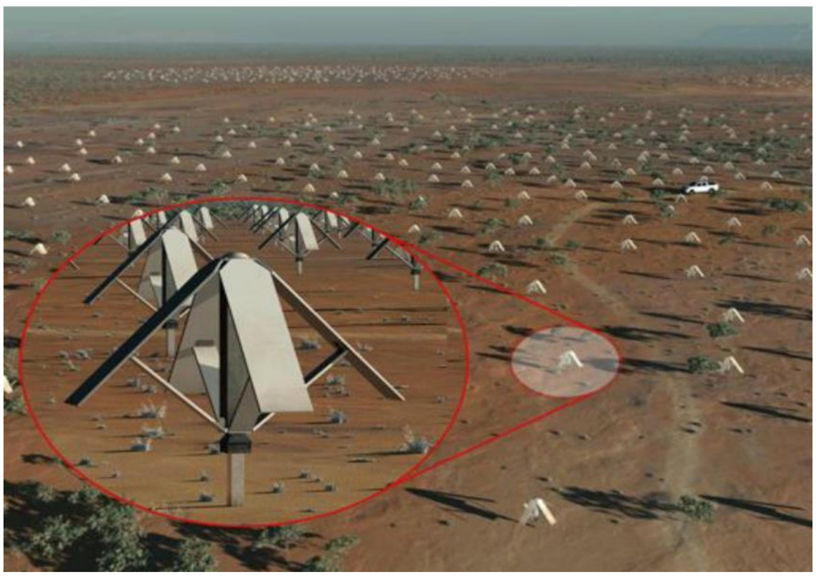

Figure 2-5 SKA -1 Concept [28].

The Square Kilometer Array (SKA) program is one of the most significant radio telescope development projects. Fig. 2-5 is an illustrated concept representing the finalized design of the square kilometer array.

The development of sparse array concepts has significantly improved the limitations that held back the dense array systems by offering ultra-wideband without loss of efficiency, eliminating any blind spots, higher efficiency due to the uniform amplitude weighting, limited effects caused by mutual coupling, and smaller beamwidths offering greater resolution.

Sparse arrays offer a wide range of capabilities that trump dense arrays, but these do not represent the pinnacle of array advancement. Sparse arrays often need digital algorithms that allow efficient beam forming and tracking, increasing the overall implementation cost. Modern sparse arrays cannot operate in the mm-wave regime primarily due to the phase uncertainty between the elements and the transmission efficiency that exists at these frequencies. Variably distanced arrays often need calibration units that match the phase between each element and sync them to a particular signal trend.

2.3 Proposed Array Architecture

As discussed in the previous section, a sparse array has its drawbacks that often make operational capability at mm-wave frequencies highly complex and expensive to implement. To alleviate the issue of phase tracking implemented at a digital level, increasing the overall complexity and the capability of aligning the elements in spatial symmetry according to the phase of the received signal. The research introduces the novel concept of the intelligent phase shifter. The intelligent phase shifter is a module placed on an antenna that is typically placed at the center of the array. The phase shifter loop estimates the phase difference of a locally generated signal concerning the received signal.

The loop then corrects the phase of the locally generated signal to that of the received signal. This correction approximates the phase offset as constantly varying DC voltages that settle once the phases are matched.

The DC voltage is then subjected to various level shifts based on the distance of the elements from the primary receiver module that tunes the antennas to the received signal phase simultaneously without the need for spatial signal processing or digital calibration.

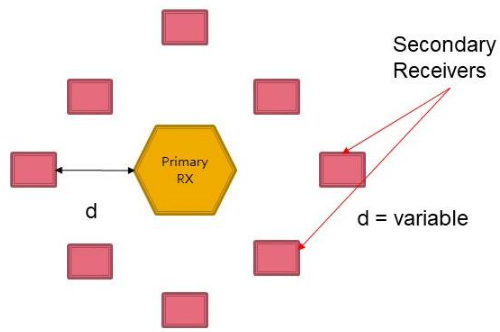

Figure 2-6 Proposed array.

The array with the new phase tracking allows for compensation and real-time calibration. PVT variations can be characterized beforehand as each element utilizes the same shifter and can be accommodated in the field.

CHAPTER 3

INTELLIGENT PHASE SHIFTER FUNDAMENTALS

3.1 Phase Shifter

Phase shifters are modules or devices that alter the phase relation of an electromagnetic signal by changing the phase angle in a two-port network. The signal is made to undergo a controllable delay due to a delay element or a combination of vectors. Phase shifts modeled as per the set of mathematical rules:

The RF input signal in the time domain:

$$X(t) = \mathrm{Sin}(wt) \tag{3.1}$$

$$X^{i}(t) = A(n)\,\mathrm{Sin}(wt + \phi(n)) \tag{3.2}$$

‘n’ is the programmed phase.

A(n) is the insertion loss.

A simple phase shifter modeled as a two-port network offers a controllable transmission phase angle between port-1 and port-2, as represented by Fig. 3.1.

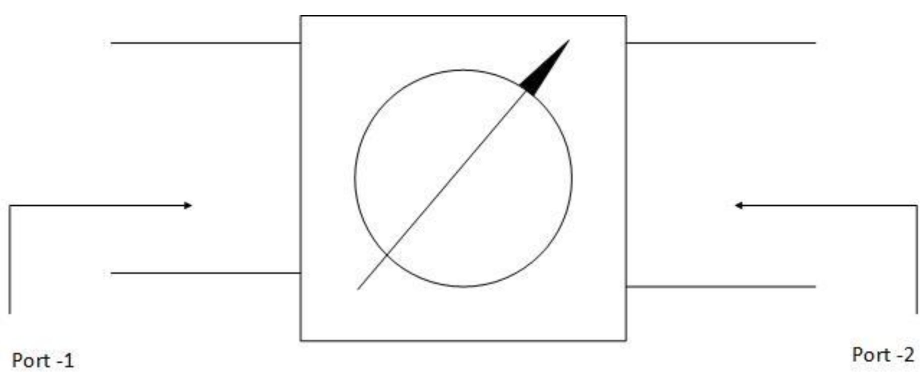

Figure 3-1 Two port representations of a phase shifter.

Phase shifters offer lower insertion loss at all the operation states, and in cases where insertion loss is significant, amplifiers can be used to compensate at the input ports of the phase shifter. Ideally, phase shifters offer a continuous amplitude over the entire controlling range. Some architectures like the vector modulator use variation in amplitudes to control the phase.

3.2 Phase Shifting Architectures

Phase Shifters can be employed at different parts of a receiver or transmitter chain. Depending on the architectural requirements, phase shifters can be classified in LO phase-shifting, RF phase-shifting, and Digital phase-shifting.

3.2.1 Phase Shifting at the Oscillator level

A typical mixer essentially results in a signal that is a subtraction of the RF frequency and the LO frequency. If the LO and RF phase is offset by '$\Delta\Phi$.,' The result is the subtraction. This architecture eliminates the need for signal manipulation at the RF level, yielding to higher noise figures or extremely high linearity requirements and loss incurred at high frequencies. LO phase shifting is impactful if the system is subjected to almost no Rf interferers. On the contrary, interferers require the mixer to possess a greater dynamic range calling for more excellent power dissipation. Fig. 3-2 is a simple representation of a phase-shifting architecture that is employed at the downconversion level.

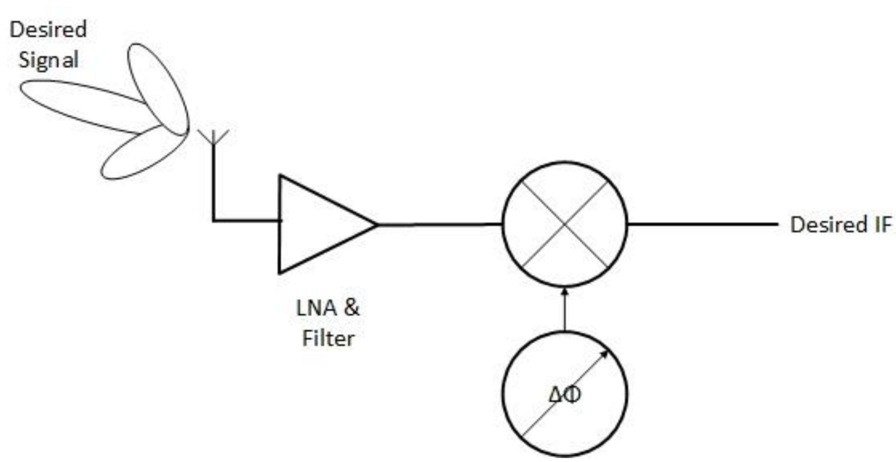

Figure 3-2 LO phase shifting.

One of the most efficient ways of introducing a controllable phase shift at the behest of low noise figures is introducing phase shift at the frequency translation level.

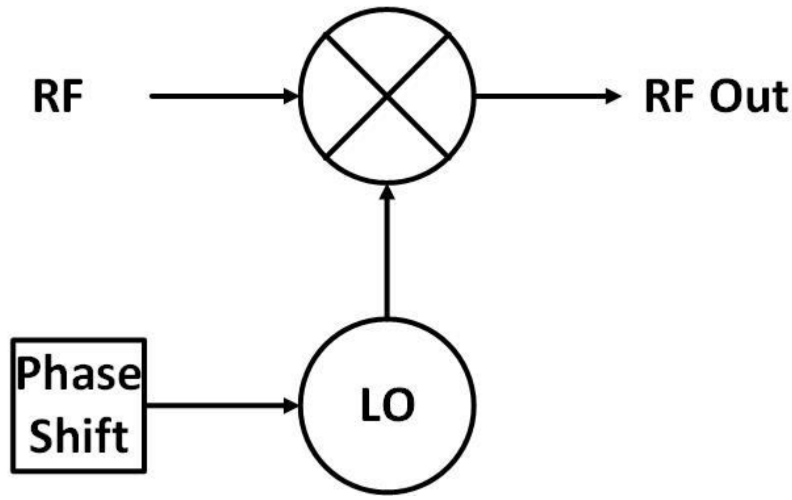

Figure 3-3 Common LO phase shifter architecture.

Fig. 3-3 represents a typical LO phase shifter. The system calls for a local phase shift module that alters the phase metrics of a frequency synthesizer. The synthesized signal translates the Frequency of an IF or an RF. The introduced phase shift is translated into beamforming receivers and transmitter modules.

These types of phase shifters are susceptible to interferers, Which puts stress on the dynamic range of the mixer. As well as modifications to the VCO that dissipates more energy than regular architectures, LO buffering is needed to reduce the load on the mixer further.

LO phase shifting offers more excellent noise immunity but at the cost of dynamic range. These phase shifters can be used in both Frequencies up as well as down translation. Each channel in the phased array requires its local oscillator, increasing the receiver module's complexity and overall power dissipation.

In order to increase the phase-shifting range, subharmonic mixers are used in the LO path. Varactor-based phase shifters in the LO loop offer controlled and wide-range shifting capabilities. Similarly, delay line elements are also used to introduce fixed phase shifts into the LO stream.

3.2.2 Phase Shifting at the RF level

RF phase-shifting systems employ the methodology of combining phase-shifted signals or vectors at the RF frequency, later mixed, and downconverter to IF. RF phase-shifting reduces the overall complexity and load on either the down-converting stage or the IF stage. The figure represents a typical RF path phase shifter.

Combining occurs at the RF stage, allowing for interferer cancellation before the signal is downconverted, requiring lesser dynamic range requirements on the mixer and the subsequent blocks. The automatic gain control of specific architectures allows for desirable amplitude control in the null patterns of an array and gives options for wideband implementations.

The blocks incur limitations during the process of silicon implementation that makes the process lossier, whereas the active phase shifters require greater linearity that allows for better accommodation of interferers. Noise levels play a significant role in the RF path. Active phase shifters are known to degrade the noise figure of the system.

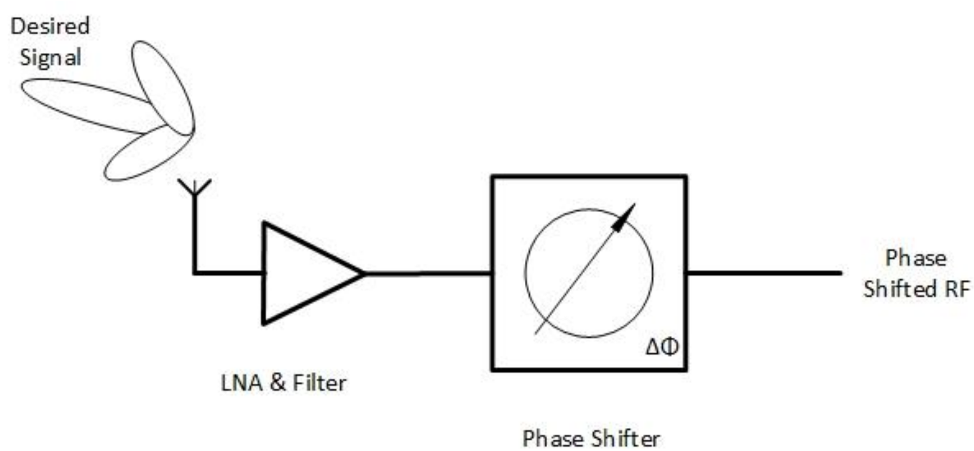

Figure 3-4 RF-path phase shifter.

One of the standard and most efficient for RF phase-shifting is the vector modulator phase shifter. This approach offers a complete 360° phase shift at the RF level at the cost of minuscule area consumption. A vector modulator is a phase shifter architecture that is based on the methodology of phasor vector summation. The objective of the vector modulator is to offer simultaneous magnitude and phase control of an RF signal.

The methodology of the device is to split the RF signal into two portions of equal amplitude but separated by a phase difference of 90 degrees. The individual signals are subjected to two independent amplifiers that either attenuate or amplify with variable weights.

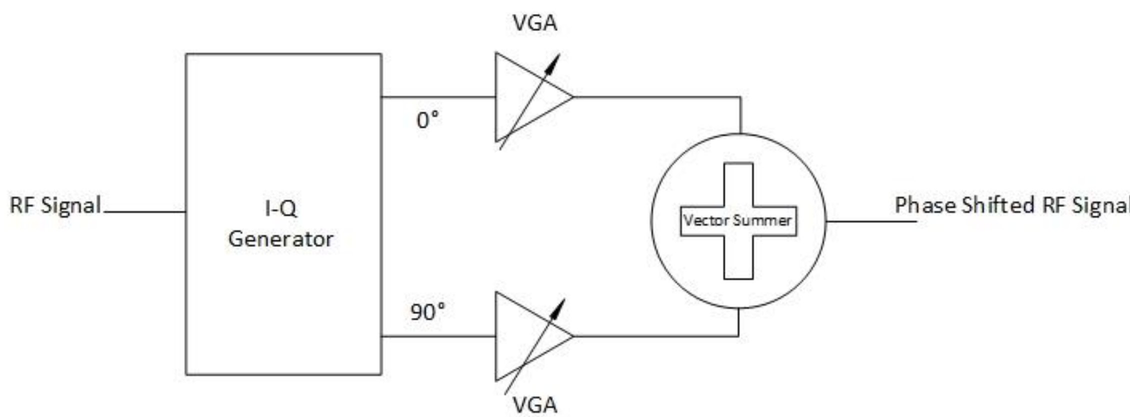

Figure 3-5 Vector modulator phase shifter.

The RF signal is split into a quadrature-phase and in-phase, the phase-shifting process is mathematically given by:

$$x_i(t) = A\,cos(\omega_r t) \qquad (3.3)$$

$$x_q(t) = A\,cos(\omega_r t + 90) \qquad (3.4)$$

The signals are subjected to individual weights and are combined:

$$y(t) = A_i A\,cos(\omega_r t) + A_q A\,cos(\omega_r t + 90) \qquad (3.5)$$

The I and Q signals are weighted individually, the resultant phase shift is

$$\phi = arctan(Aq/Ai) \tag{3.6}$$

The signals are then combined actively or passively to complete the summation of two phasors that yield a resultant phase shift. If the control signals are maintained at a constant level, the vector modulator phase shifters offer a constant, often an arbitrary phase shift.

Table Represents the mathematical model representing the vector modulator phase shifter and a standard design guide based on the impact of applying individual weights to the I and Q RF paths.

Table1

Theoretical Phase Shift Model

Bi-Phase Modulator States I	Q	Desired Phase Shift
0	0	0-90
180	0	0-180
180	180	180-270
0	180	270-360

The phase shifter is preferred due to its integration capability and silicon implementation capability. As this phase shifter primarily relies on active devices for phase-shifting, the device is often plagued by poor linearity, high power consumption, and noise figures.

3.2.3 Phase Shifting at the Digital level

Digital Arrays employ the process of incorporating the required phase shift in the digital realm. The RF signal is down-converted, or directly RF sampled. Phase shits and correction in the digital domain typically use a Digital Signal Processor (DSP). This type of phase-shifting requires the ADC and the mixer to possess a very high dynamic range, increasing the complexity and the overall power dissipation of the entire design.

The main advantage of digital arrays is the amount of utility that it offers. This is due to the ability to implement a wide range of signal processing algorithms in the digital realm. Many iterations can be, and algorithm refining as well can be incorporated on the fly.

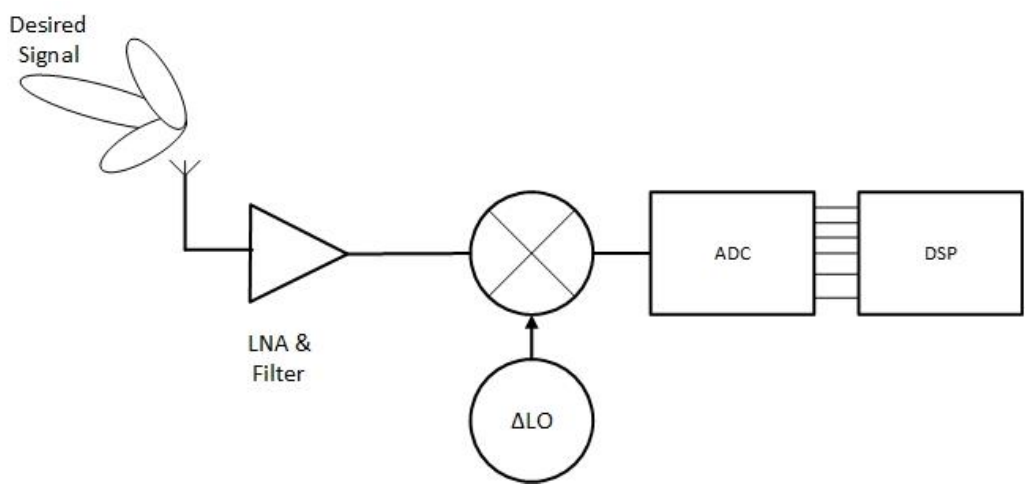

Figure 3-6 Digital phase shifter.

Any interferes that tends to be notorious for the overall communication system is eliminated using spatial signal processing. The introduction of these algorithms is often referred to as intelligent antenna systems. Due to the systems’ reprogrammability, such technology is used in portable wireless systems like mobile phones and portable encrypted communication devices.

3.3 Phased Detector

A phase detector is a device that compares two waveforms and yields an output that is proportional to the phase difference between the signals represented by the mathematical term $\Delta\phi$.

$$\Delta\phi = \phi 1 - \phi 2 \tag{3.7}$$

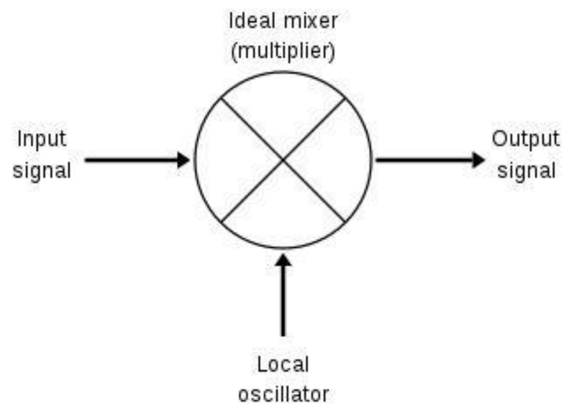

Figure 3-7 Frequency translation mixer.

The basic concept that governs phase detection is that two signals with identical frequencies and constant amplitude are applied to a mixer, resulting in a DC output proportional to the phase difference between the two signals.

The mixing process is mathematically modeled demonstrated as follows.
The local oscillator port is excited by the signal x(t), which is typically a reference signal:

$$x(t) = Ax \sin(Wx * t + \phi x) \tag{3.8}$$

The RF reference w(t) is applied port-1 or (RF port) down-converted to a lower intermediate frequency or the DC signal.

$$w(t) = Aw \sin(W * t + \phi w) \tag{3.9}$$

The RF and LO signals are multiplied in the frequency domain, generating two spurs at LO-RF and at LO+RF.

$$\mathrm{Y(t)} = \mathrm{Aw}\sin(\mathrm{W} * \mathrm{t} + \phi\mathrm{w}) * \mathrm{Ax}\sin(\mathrm{Wx} * \mathrm{t} + \phi\mathrm{x}) \tag{3.10}$$

$$= \frac{1}{2}\mathrm{AwAx}\,\{\sin((\mathrm{Ww} + \mathrm{Wx}) * \mathrm{t} + \phi\mathrm{w} + \phi\mathrm{x}) + \sin((\mathrm{Wx} - \mathrm{Ww}) * \mathrm{t} + \phi\mathrm{x} - \phi\mathrm{w})\}$$

$$Wx = w + \frac{1}{2}\Delta w \tag{3.11}$$

$$Ww = w - \frac{1}{2}\Delta w \tag{3.12}$$

The Resultant signal is filtered out, separating the lower bound and upper bound components. The signal level is proportional to the phase difference between the two signals and their corresponding amplitudes.

$$\mathrm{Y(t)} = \frac{1}{2}\mathrm{Aw} * \mathrm{Ax}\sin(\Delta\mathrm{wt} + \phi\mathrm{x} - \phi\mathrm{w}) \tag{3.13}$$

The mixer output is filtered such that the $\Delta\mathrm{wt} = 0$ and the resultant phase difference are estimated as so, yielding phase detector operation.

$$\mathrm{Y(t)} = \frac{1}{2}\mathrm{Aw} * \mathrm{Ax}\sin(\phi\mathrm{x} - \phi\mathrm{w}) \tag{3.14}$$

The mixer-based phase detectors offer robust phase determination capabilities at mm-wave frequencies and beyond. The design must ensure that the load filter has a perfectly tuned load that does not allow harmonic elements to seep through.

CHAPTER 4

CMOS IMPLEMENTATION

Modern RF systems call for fully integrated systems with minuscule area requirements. Incorporating arrays of sizes that occupy very little space is the way moving forward for next-generation communication systems offering seamless transmit and back compatibility capabilities, offering better noise and interferer immunity.

This research focuses on a new phase shifter that offers phase correction enhancing beamforming capabilities phased array systems, especially for portable wireless modules.

4.1 Proposed Phase Shifter Architecture

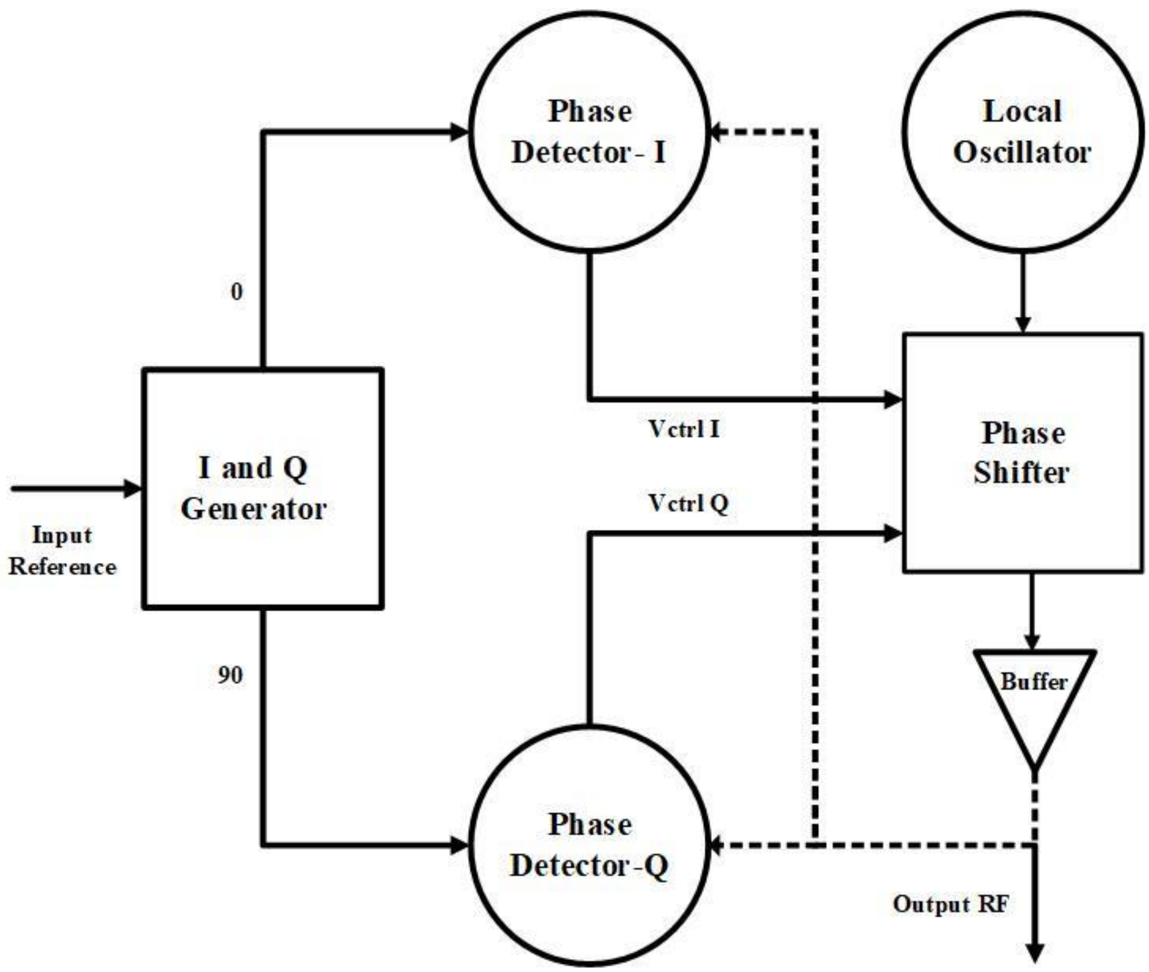

Figure 4-1 Proposed phase shifter architecture.

The main objectives of the proposed architecture are 1) Design a high-frequency phase detector with the capability of rejecting any AM modulation from the supply. 2) Continuous complete 360 control RF-Phase Shifter 3) Output impedance and magnitude correction buffer.

4.2 Phased Detector Development

The primary objective of the phase detector is to estimate the phase difference of two signals by the process of frequency downconversion. The phase detector comprises three components: Mixer, Filter, and Combiner Amplifier.

4.2.1 Mixer and Filter

The proposed phase detector incorporates a double-balanced mixer architecture. A double balanced mixer utilizes four switching devices, two each for the LO and the RF ports. This distribution of inputs offers higher RF to IF and LO to IF isolation, thereby suppressing spurious products at the down-converted port.

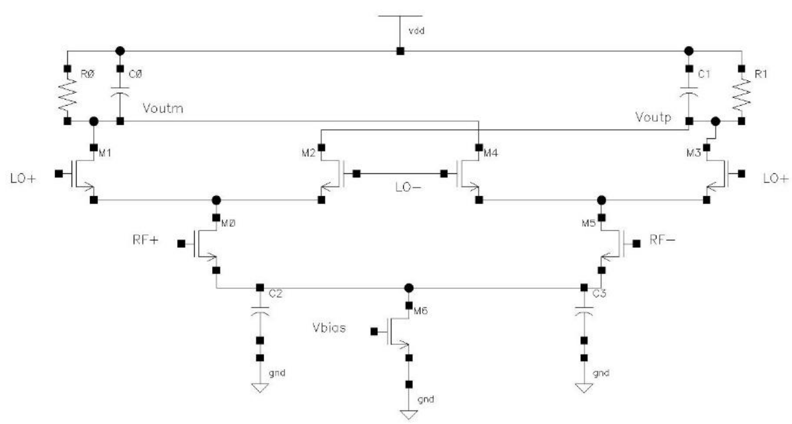

Figure 4-2 Frequency mixer schematic.

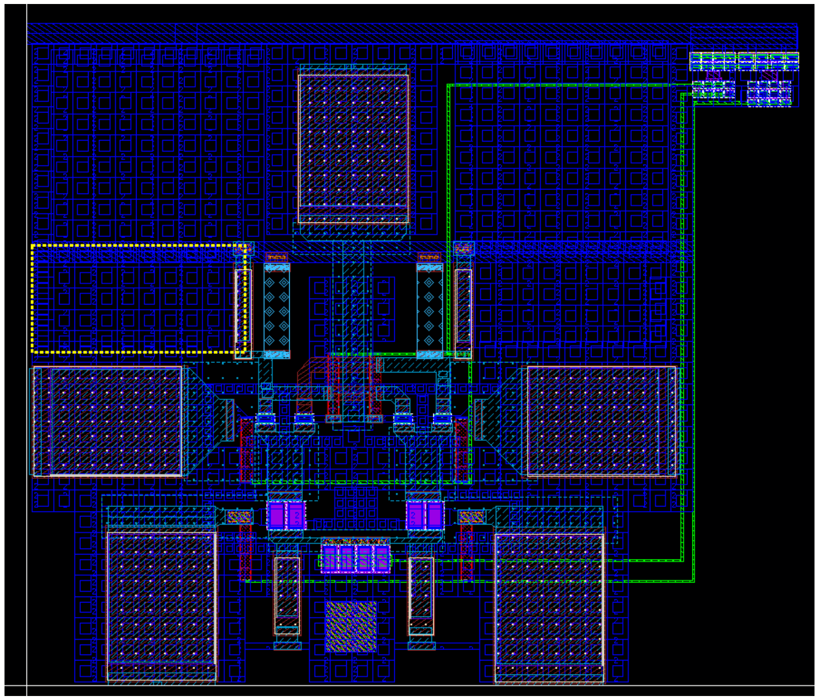

Figure 4-3 Frequency mixer layout.

The second portion of the phase detector comprises a low-pass RC filter that suppresses all high-frequency components and passes only the (low frequency - 0Hz) DC component. Fig. 4-2 illustrates the transfer characteristics of the analog multiplier-based phase detector. The phase detector offers phase detection at RF frequencies without the need for frequency division networks. The advantages offered are counteracted by the fact that the phase shifter locks only when a phase of 90^{o} offsets the two references [7].

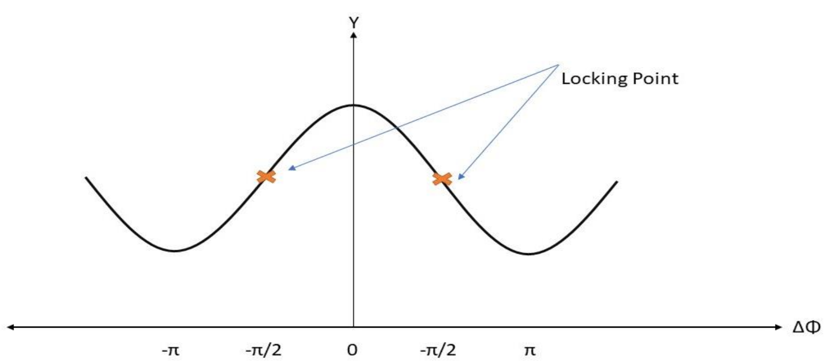

Figure 4-4 Phase detector transfer function.

Fig. 4-3 represents the phase detector transfer curve generated for a reference signal centered at 28GHz. A transient simulation spans over 10ns with the signal phase varying from 0^{o} to 360^{o} in steps of 45^{o} every 1ns.

The proposed design incorporates a low pass filter whose time constant is estimated to be:

$$\tau = RC \tag{4.1}$$

The figure has the differential outputs centered at DC. As per the transfer characteristics discussed in the previous section, the architecture follows the trigonometric transfer characteristic following the applied signal [7].

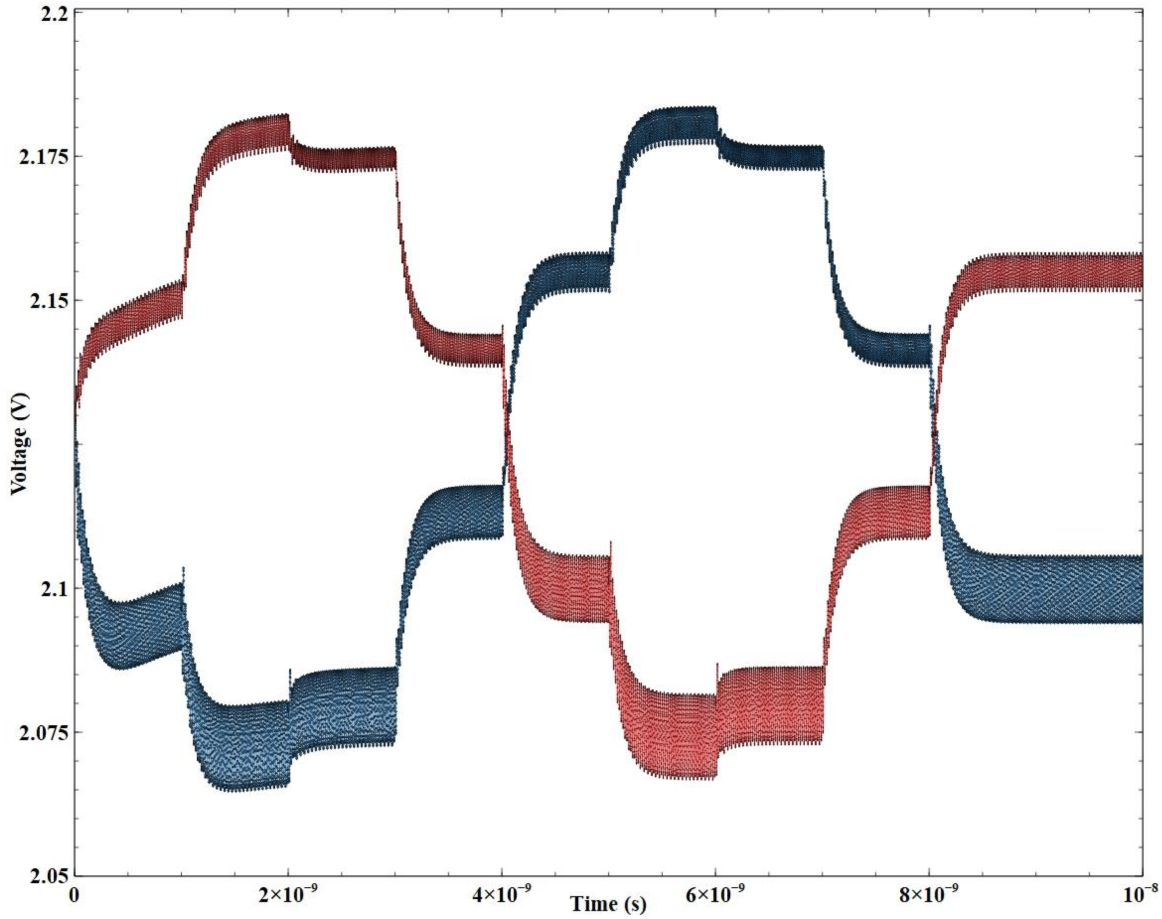

Figure 4-5 Mixer transient simulation.

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4.2.2 Operational Transconductance Amplifier

The OTA is an operational amplifier that offers the voltage to current conversion. The device calculates the difference between two input voltages and generates a proportional current. The current mirror approach provides the capability to drive greater impedance loads without the need for buffering stages. Fig. 4-3 is the schematic representation of the OTA. The ideal OTA offers a lower gain to meet the amplification requirements. A wide swing cascode approach is chosen to increase the overall voltage gain by 20dB from the typical 40dB to 60dB. The cascading current mirror at the outputs increases the gain by actuating the output impedance.

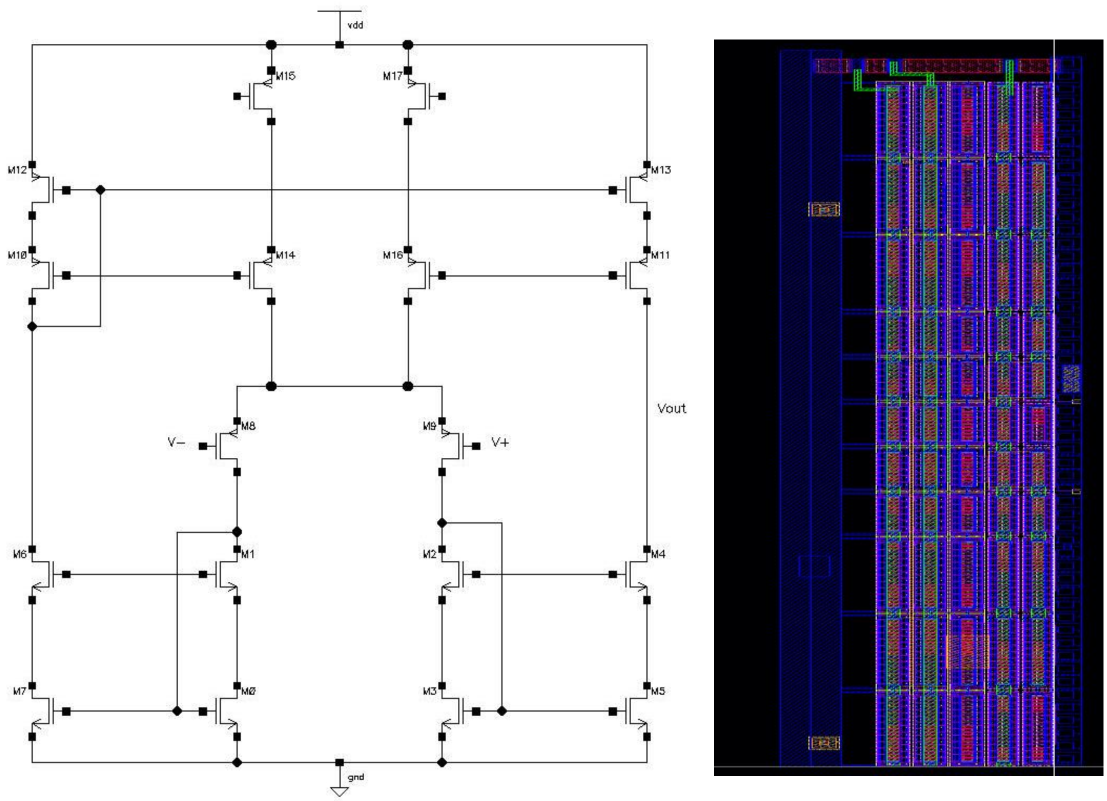

Figure 4-6 a) Cascode operational transconductance amplifier schematic. b) Cascode operational transconductance amplifier layout

The voltage gain of a cascode OTA is a parallel combination of the output impedance proportional to the gain by a factor of the input device's transconductance capability.

$$A_v = gm(R_{caspn}||R_{casp}) \tag{4.2}$$

The pole offers a 3dB reduction in the gain, and this is modeled as:

$$F_{3dB} = \frac{1}{2\pi(R_{caspn}||R_{casp})C_L} \tag{4.3}$$

The unity-gain bandwidth as a function of output current and load capacitance:

$$F_{un} = \frac{gm}{2\pi C_L} \tag{4.4}$$

Any increase in the load capacitance reduces the unity gain of the OTA, resulting in more excellent stability. The differential OTA smoothens any perturbations generated at the differential outputs of the detection mixer during lock-in conditions. The amplifier also gains the signal to ensure full swing to offer better phase control at the phase shifter level.

Fig. 4-4 represents the performance metrics of the amplifier, offering a gain of 70dB, and bandwidth of Hz offers optimal performance perfect for the amplification. Due to the cascode architecture, AM modulation effects due to the presence from the supply rejected showing clean amplifications.

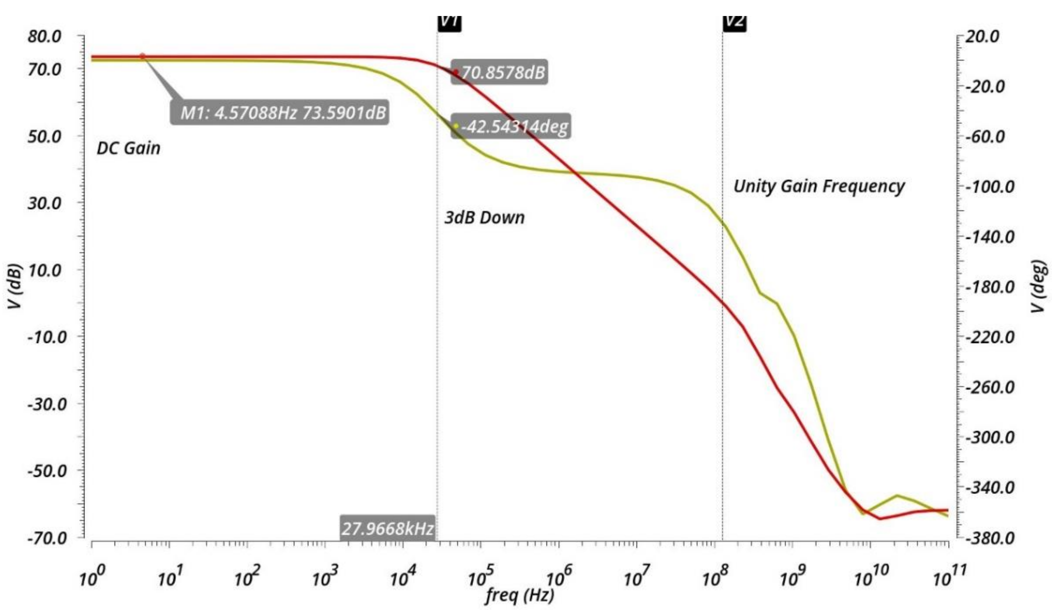

Figure 4-7 OTA AC response.

Table 2

OTA performance metrics

Gain (dB)	73.3
Power Dissipation (mW)	3.6
Unity Gain Bandwidth (Hz)	130M
3dB Bandwidth (Hz)	31.4K
Phase Margin (°)	56

4.2.3 Phase Detection with OTA Smoothening

Fig. 4-5 is the illustration of the complete phase detector with the OTA. The modification offers the combination of the differential amplifier and negates any perturbations that simultaneously occur on the differential outputs. The smoothening is also applicable to AM modulation rejection. Suppose the power supply oscillations are treated as common-mode and eliminated.

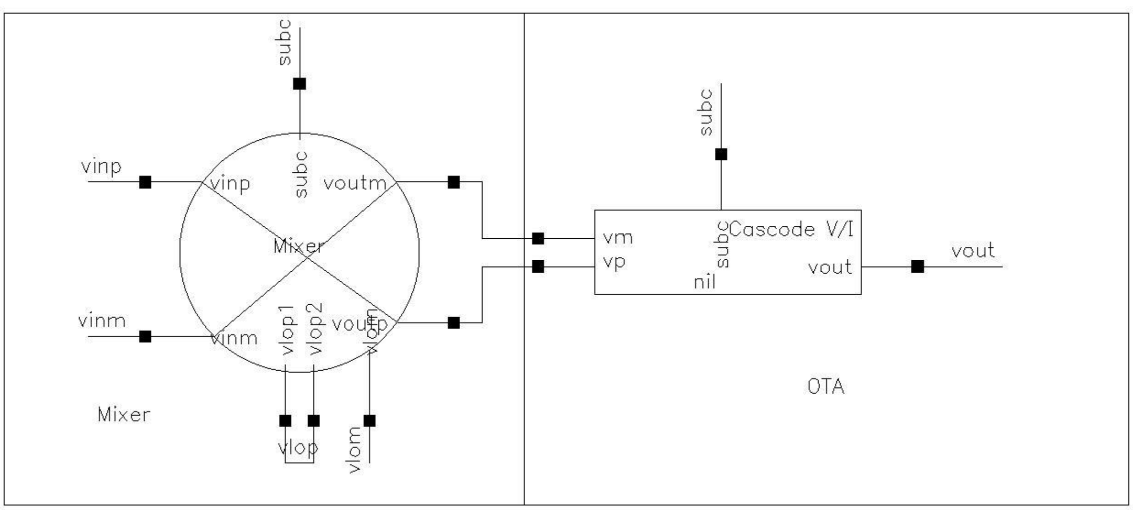

Figure 4-8 Phase detector with OTA smoothening.

The combination of the mixer and the OTA offers a total gain is equal to two cascade amplifiers in series.

$$A_{ToT}(dB) = A_{m_ix}(dB) + A_{0TA}(dB) \quad (4.5)$$

The phase offset is translated to a differential DC voltage, and this voltage possesses low swing and ripples translated from the constant variations due to the frequency of the applied RF signal.

The OTA estimates the difference between the two differential inputs and eliminates the ripples as they are treated as common mode at the output of the amplifier. The difference is gained by 70dB over a four-volt supply to conform with the tuning range of the phase shifter. Fig. 4-8 illustrates the smoothened signal that is generated. We can also observe that the signal follows the transfer function described in section 4-1.1

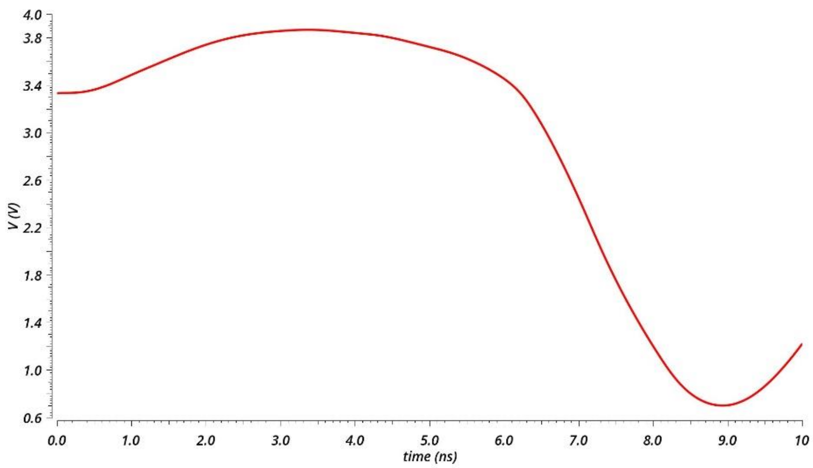

Figure 4-9 Detector transfer function after smoothening.

4.3 In-phase and Quadrature-phase detection.

The phase shifter offers a dual input continuous-time phase-shifting capability. To forgo any ambiguity that is entailed with phase detection, two-phase detectors are introduced into the loop to offer complete control of the phase shifter and avoid any discrepancy that comes with the detecting quadrature components in the loop. I-phase and Q-phase detection comprise two stages, Quadrature generation, and detection.

4.3.1 Quadrature Signal Generation

In order to offer better tracking, the system incorporates a Quadrature signal generator. The system employs a single-stage RC polyphase filter operating in the voltage mode. The R and C are selected accordingly to offer a 50Ω impedance at the four inputs of the phase filter and similarly offer a 50Ω output termination impedance. Fig. 4-9 represents the polyphase filter designed keeping in mind process variations and ease in layout implementation [5].

The polyphase filter in this situation offers perfect quadrature phases at the behest of image rejection. Image rejection can be incorporated in future iterations of designs.

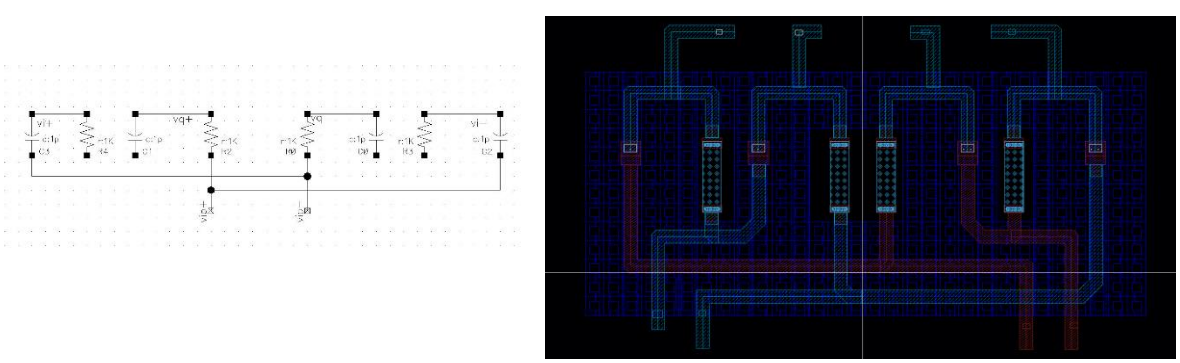

Figure 4-10 a) Poly phase filter schematic. b) Poly phase filter layout.

Fig. 4-10, Represents the transient simulation of the quadrature generation circuit. Each input to the filter offers 50Ω at the input. The differential signal is equally divided amongst the two pairs of input ports. The output ports maintain the same amplitude, but the phases of the signals are divided into quadrature differential signals.

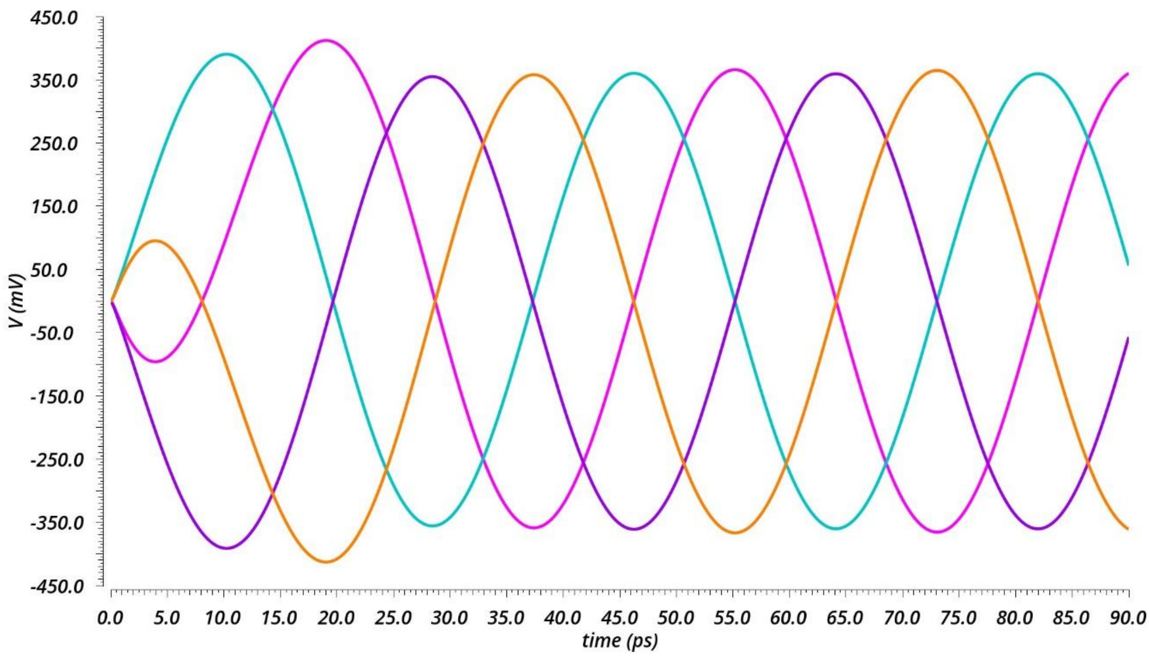

Figure 4-11 Polyphase filter transient response.

The polyphase filter incorporates decimation and interpolation algorithms based on spatial signal processing. The filter develops a notch-based response at the center frequency that is dictated by the equation.

$$f = \frac{1}{2\pi RC} \tag{4.5}$$

The polyphase filter is commonly used for narrowband rejection. Narrowband rejection is achieved by splitting a signal into quadrature poly phases. This ability of the filter can be repurposed to generate quadrature signals.

4.3.2 Phase Tracking System

Phase detection comes with ambiguity in determining the phases that exist in the quadrature part of the phasor circle (90^{o} and 270^{o}). To alleviate this ambiguity, we go for a two-phase detector approach, one that compares the pure reference while the second detector compares with a reference that is phase shifted by 90^{o}. Fig. 4-12 represents the phase detector setup that tracks the signal at all phase instances.

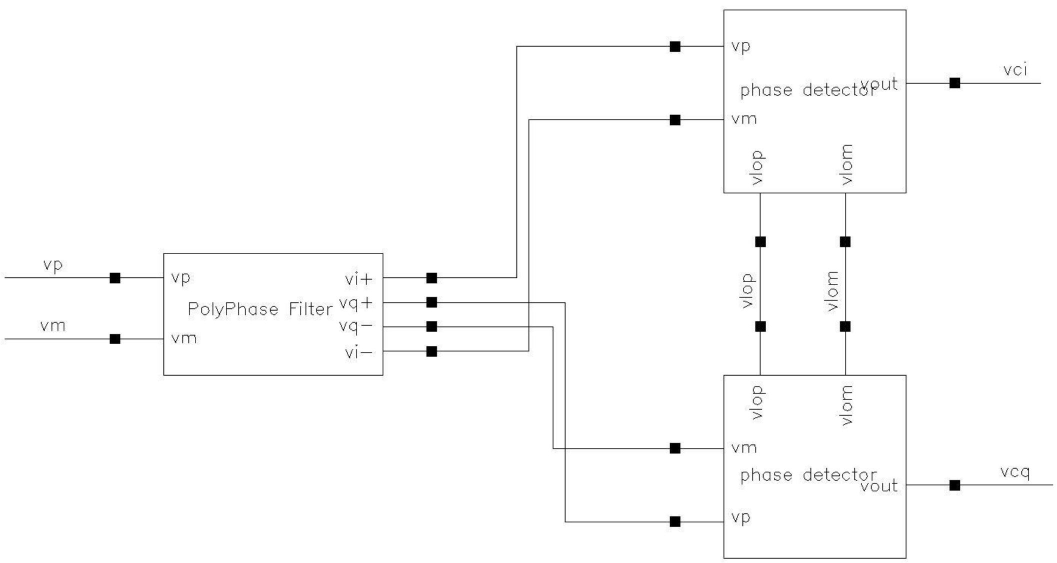

Figure 4-12 Phase tracking unit schematic.

The phase-detection system is simulated over a transient simulation of 10ns. The phase of the input reference signal is shifted by 45^{o} every nanosecond. Fig. 4-12 shows the simulation where two signals VCI and VCQ, that follow the typical detector transfer function are generated from the detector module.

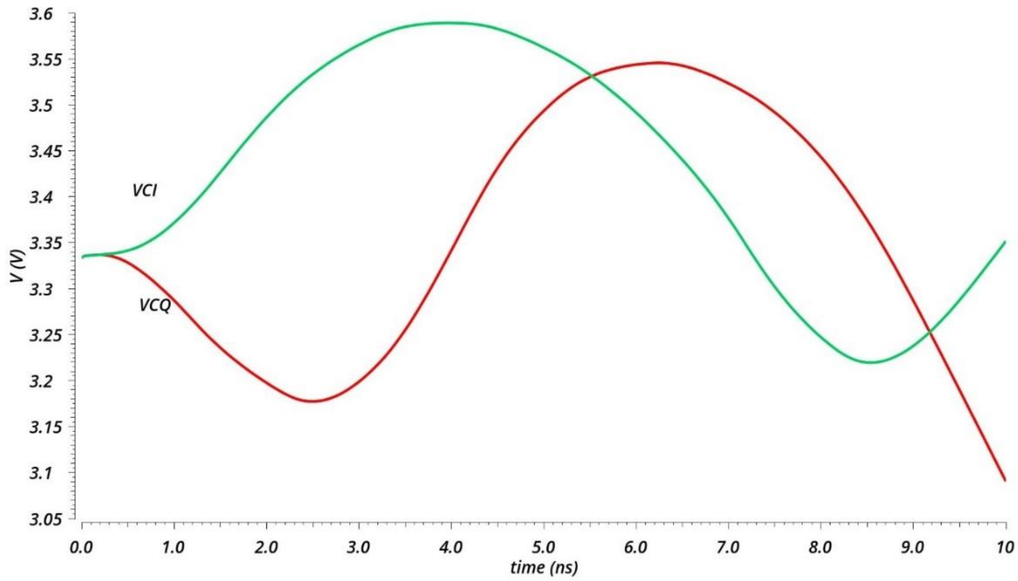

Figure 4-13 Phase tracking transient unit simulation.

4.4 Vector Modulator Phase Shifter

Vector modulators have become a standard architectural choice for high-frequency phased arrays and RF level phase-shifting systems that offer 360^{o} phase shift while offering reduced area consumption and very high integration capability [3]-[4]. The vector generation and summation in the current domain. In the architecture described, fully differential signals fed into the core generate quadrature current signals through polyphase filtering. The signals summed up the current domain offer tunable phase and magnitude.

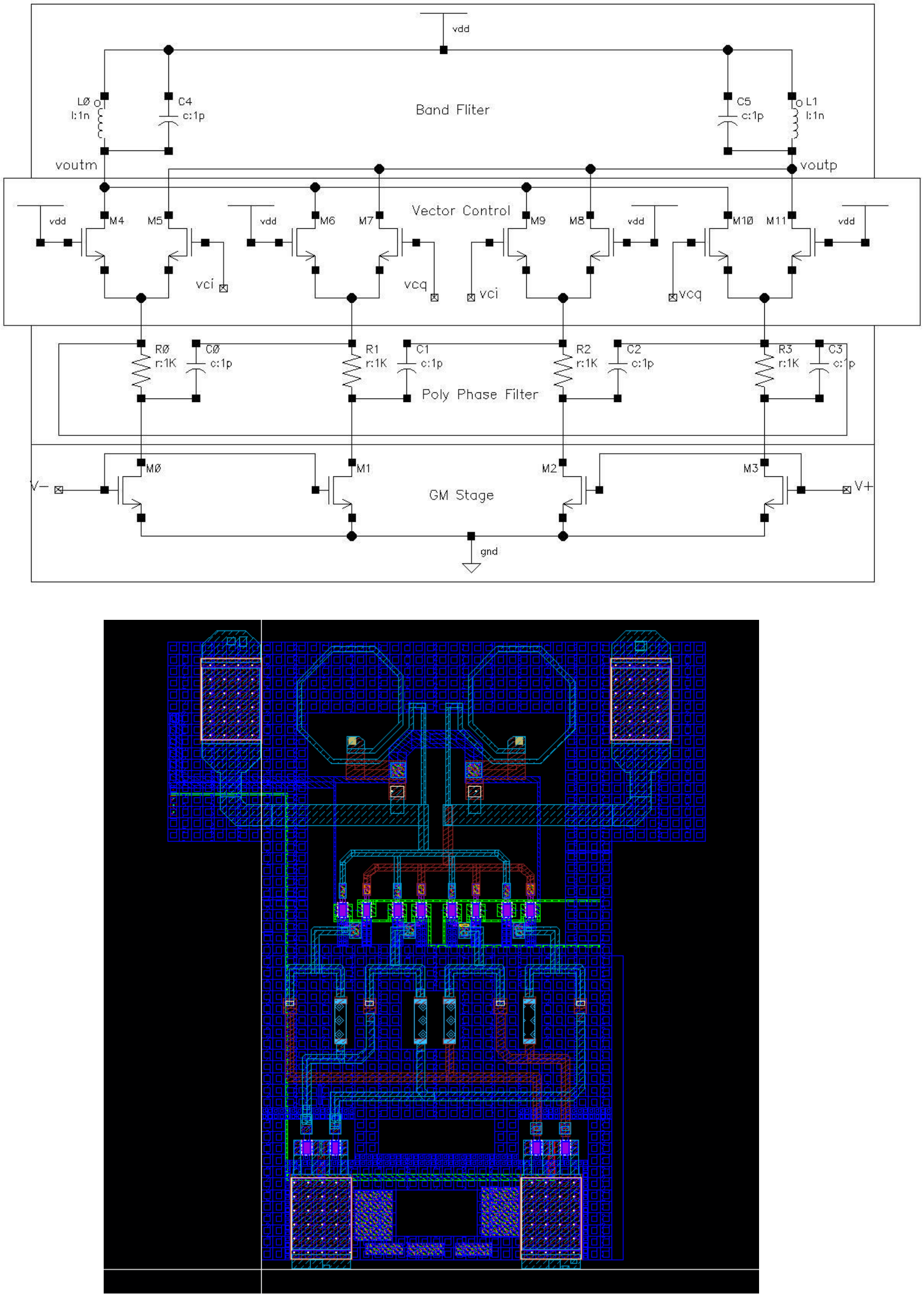

Figure 4-14 a) Vector modulator schematic, b) Vector modulator layout.

The transconductance stage (GM stage) forms the core of the vector generation module, and These devices convert the applied RF signal into a current proportional to the GM of the transistor. Transistors M0 to M3 generate a similar proportional current due to the symmetric sizing of these devices. A polyphase filter operating in the current mode is selected to offer low impedance paths for the RF currents and equally distributed magnitudes across the four-vector outputs of the filter. An array of 8 transistors (4 pairs) placed in the gilbert cell fashion offers optimal current magnitude control required to achieve the desired phase shift. The eight devices (M4 to M11) possess the same device physical characteristics to maintain similar bias currents across and small-signal parameters at all the legs of the module. The shifter also accommodates for harmonics and out-of-band signal elimination with the help of an L-C band filter in the RF choke configuration, providing the required DC bias and offering gain peaking at the desired center frequency [6].

This design offers the advantage of utilizing only two control voltages, VCI and VCQ, controlling the magnitude of the in-phase and quadrature-phase components, respectively.

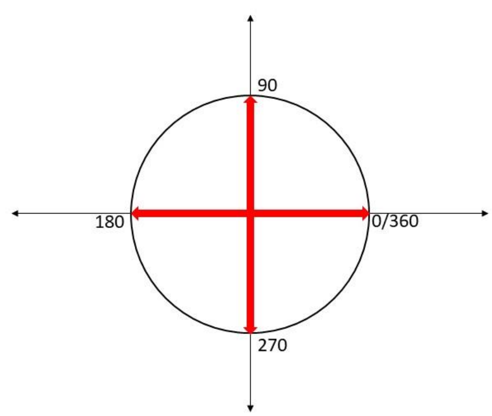

Figure 4-15 Vector Locations for the phase shifter.

The phase shifter follows the methodology of generating four-vectors, with each vector (arrows in red) being spaced 90° from each other on the phasor circle as represented by Fig. 4-14. Each phase is summed in the current domain, yielding a phase shift of 90° in the idle condition when no excitation voltage is applied to each magnitude control input.

Fig. 4-13 shows the phase shifter's simulated S11 (input insertion loss) using cadence. The magnitude of the phase shifter shows an input matching of -22dB at 28GHz, with the VCI and VCQ control voltages swept over the entire control range.

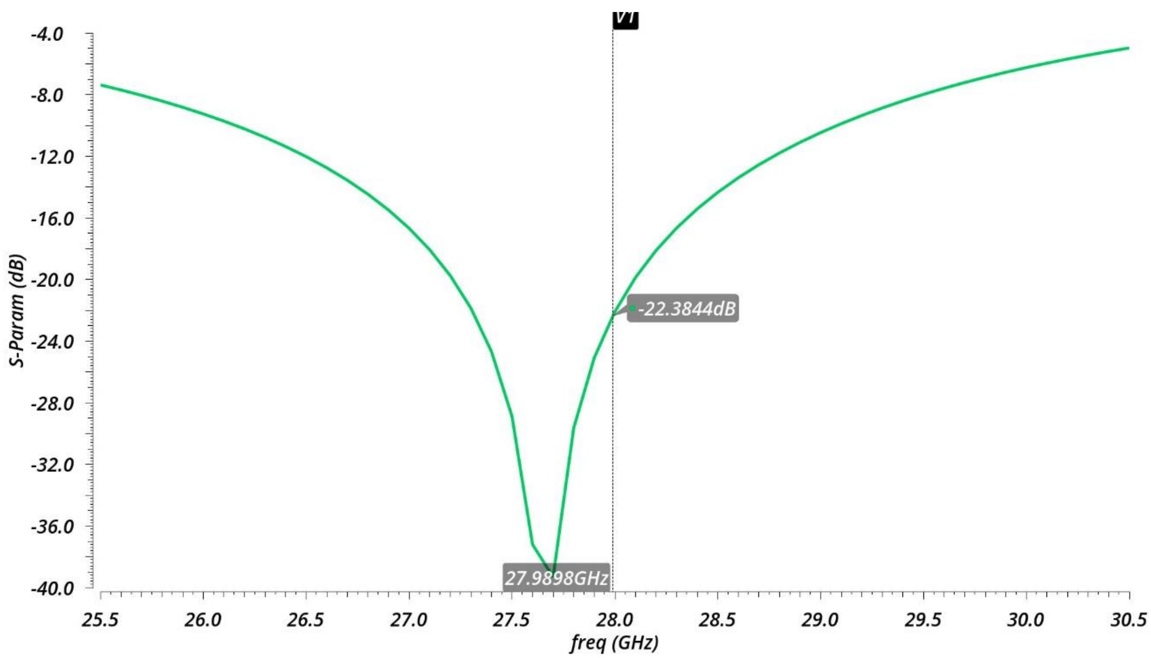

Figure 4-16 Vector modulator phase shifter.

S_{21} or the transmission parameter is represented in Fig. 4-14, with similar control voltages being swept over the entire range. We observe that the phase shifter offers 360° shifting capability over 5GHz band with peak performance-centered at 28GHz.

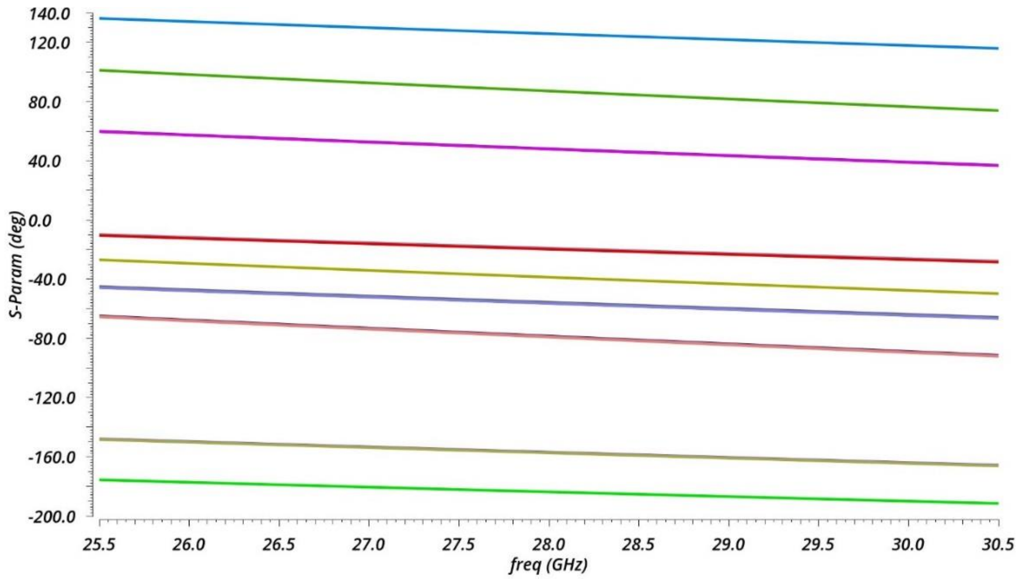

Figure.4-17 Vector modulator phase shifter.

The performance metrics of the phase shifter are tabulated in Table.2. We observe that the phase shifter offers optimal performance at the specified center frequency

Table 3

Vector Modulator Performance Metrics

Frequency	GHz	28
Phase Tuning Range	Degrees	360°
Power	mW	88
Tuning Resolution	-	Continuous
Gain	dB	-6 ±3

CHAPTER 5

SIMULATION AND RESULTS

The previous section developed the design considerations for the development of the entire phase correction loop. Where each component was explored in detail, and a comprehensive overview of their capabilities was discussed.

5.1 Schematic Level Integration and Simulation

Fig. 5-1 shows the schematic setup of the proposed phase correction architecture in cadence. The time to lock, noise factor, and phase correction accuracy are simulated across all PVT conditions. The phase shifter elapses a total of 285nS to lock to a particular phase shift introduced at the loop's reference input. The loop functions closely to its frequency counterpart, the phase-locked loop.

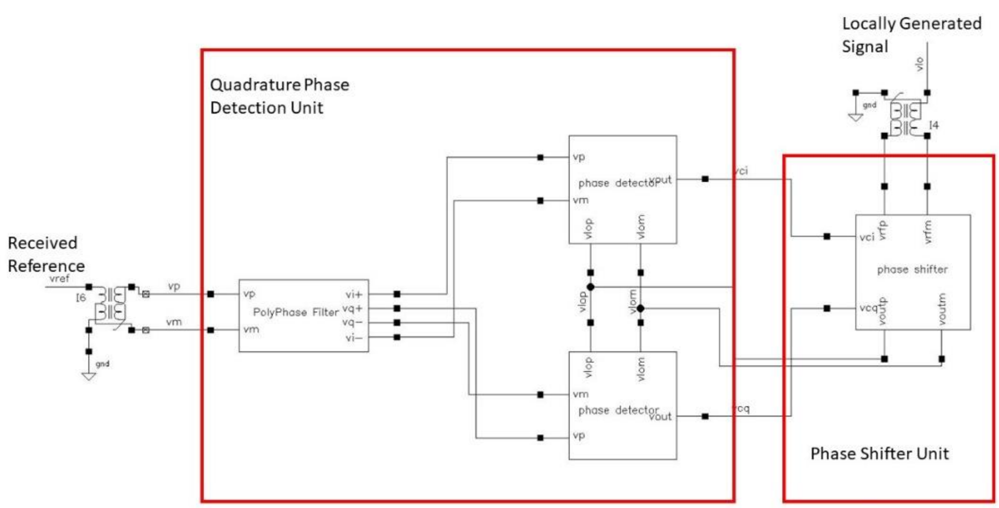

Figure 5-1 Intelligent phase shifter top level schematic.

Fig. 5-2 and 5-3 show the results achieved via a 10µs transient simulation where the phase of the input reference offsets at a rate of 45° every µs, allowing for optimal locking and estimation of loop instabilities over more prolonged periods after the loop settles to a particular control voltage.

The loop has built-in impedance buffering amplifiers that reduce any reflections that occur from the feedback loop.

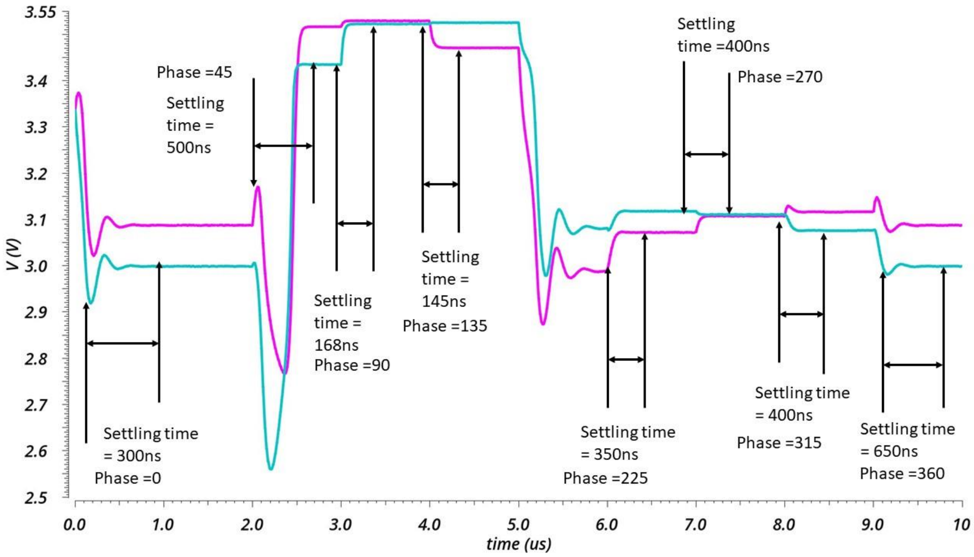

Figure 5-2 Transient simulation showing control voltages.

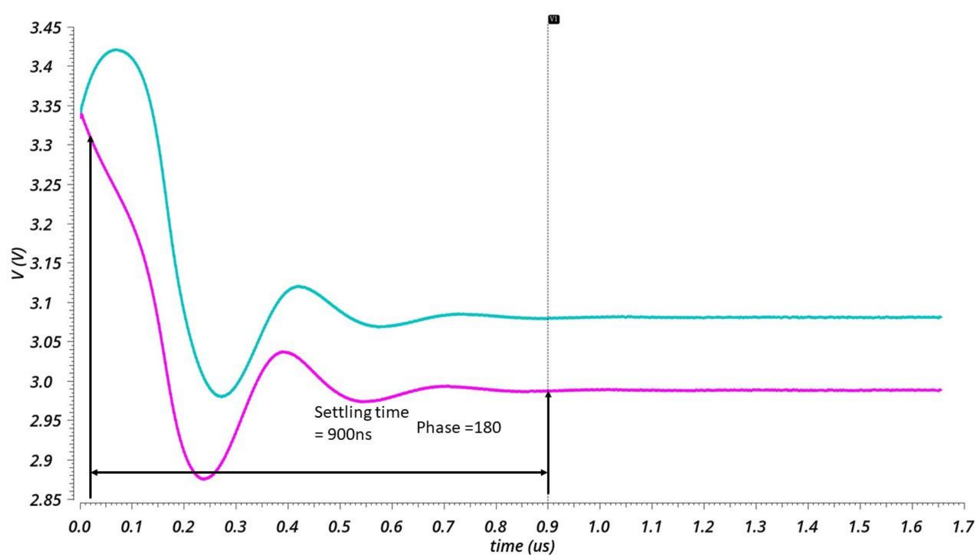

Figure 5-3 Transient simulation of control voltage stabilization.

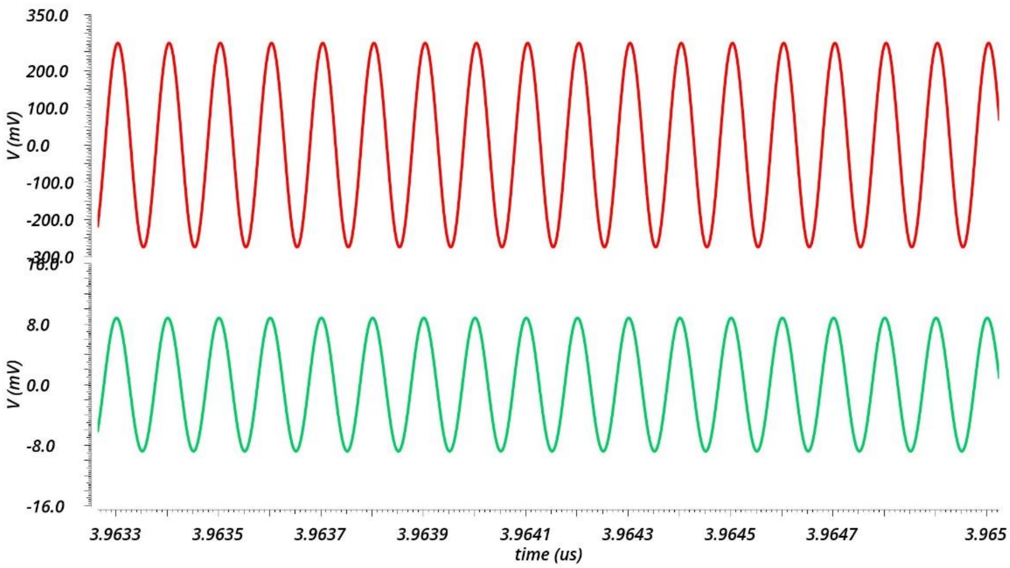

Figure 5-4 Transient simulation showing phase match.

5.2 Layout

The entire system is developed on the Global Foundries 8XP platform. Fig. 5-5 represent the physical implementation of the loop that is currently in the fabrication process.

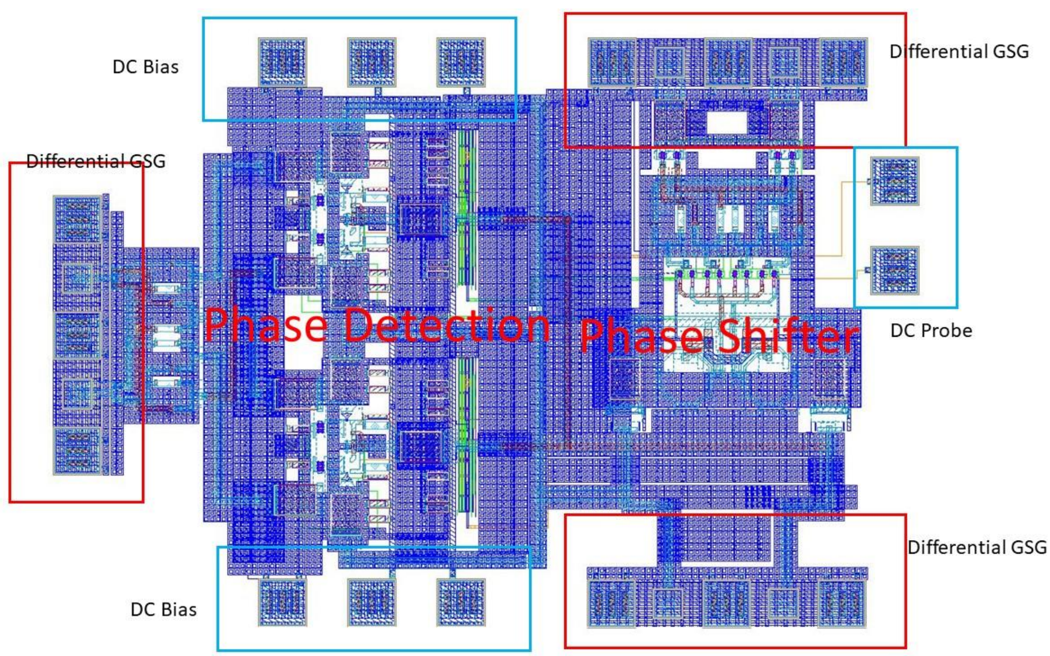

Figure 5-5 Intelligent phase shifter layout.

CHAPTER 6

CONCLUSION AND FUTURE WORK

This thesis has exhibited a fully capable phase detection and correction methodology in high-frequency phased array environments. Modern communication systems call for faster data rates, often dependent on higher bandwidth, which increases phase ambiguity. The simulations prove that any phase ambiguity can be detected and corrected.

The intelligent phase shifter is undergoing fabrication on 120nm Bi-CMOS technology. Simulated results show that the phase shifter offers complete 360^o phase shifting at 28GHz. The intelligent phase shifter operates on a 3.5V supply for the RF components and a 4V supply for the OTA to achieve a complete phase shifter tuning range. The architecture dissipates a total of 378 mW offering perfect phase-matching but with a DC offset of 90^o. The offset is due to the inherent lock-in section of an analog multiplier phase detector that dictates the lock occurs if the two signals are a quadrature-phase apart. The phase-shifter loop demonstrates phase tracking and locking over the entire input phase shift range from 0^o to 360^o

This research points towards a new and unique research space that offers several potentials for future work. The performance of the circuit needs characterization. Upon completion of this stage, future steps would be to incorporate this phase-shifter into an array and test receiver modules placed at variable distances.

Finally, the phase shifter is simulated over a simple transient simulation for 10μs. In dynamic parameter testing, the phase of the applied RF signal is changed from 0^o to 360^o in steps of 45^o separated at 1μs. Similarly, S-parameter simulations also estimate noise performance is in conjunction with optimal phase shifter performances.

6.2 Challenges and Future Work

The innovative loop proposed in this work offers perfect phase detection. With the innovations in mind, there is always room for improvement. Several challenges are considered for future improvements:

- Testing device over wide temperature ranges and estimating phase tracking as and matching capability.
- Integrating the phase tracking and correction capability into full-fledged phased arrays.
- Investigating the development of low power and more compact iterations on lower CMOS process nodes.
- Implementing Built-in-self testing) BIST modules to achieve higher phase correction accuracy.
- Modify loop for lower lock-in time and more accurate phase matching
- Measurements of the prototype and comparing the results with simulations.

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