Broadband and Tunable RF Phase Shifter

A THESIS

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by
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Broadband and Tunable RF Phase Shifter** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2024 to May 2025. This thesis has been submitted under the supervision of Dr. Rinkee Chopra IIT Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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Dr. Rinkee Chopra

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Shivam Chaudhary

Abstract

This thesis explores the design, simulation, and analysis of broadband and tunable RF phase shifters for next-generation wireless and radar systems. As demands for wideband, reconfigurable, and compact RF components grow in 5G/6G networks, phased-array antennas, and radar systems, phase shifters have emerged as critical elements enabling beam steering and signal control. This work investigates various phase shifter architectures and presents two primary design approaches: a broadband phase shifter utilizing weakly coupled microstrip lines, and another employing multimode resonators with λ/4 stubs to achieve 90° phase shifts over a wide frequency range. Both designs were implemented on single-layer substrates to ensure low cost, minimal insertion loss, and planar integration.

Additionally, the thesis proposes compact filtering phase shifters capable of simultaneously achieving phase control and frequency selectivity. Two such designs—a 45° and a 90° phase shifter—are developed using stepped-impedance lines and open-circuited stubs, demonstrating high return loss, low insertion loss, and stable phase performance over wideband ranges. Simulation results validate the proposed designs, highlighting their feasibility for integration in advanced RF systems requiring precise phase shifts with compact, efficient layouts. This work contributes to the development of passive, low-loss, and frequency-agile phase shifters suitable for scalable RF front-ends and modern communication infrastructures.

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Chapter 1: Introduction

1.1 Background

In the era of rapid technological evolution, wireless communication systems and radar-based applications are experiencing transformative growth. The foundation of this transformation lies in the ability to transmit, receive, and manipulate electromagnetic signals efficiently. Among the critical components enabling this functionality is the RF (Radio Frequency) phase shifter. RF phase shifters are essential in systems requiring phase modulation, beamforming, direction finding, and signal control. Their importance has surged with the advent of advanced applications such as 5G/6G wireless networks, satellite communications, electronic warfare systems, and intelligent transportation systems.

Historically, RF systems operated within narrow, dedicated frequency bands. As communication and data requirements grew, the demand for systems capable of operating over broader frequency ranges increased. This has led to a rising need for broadband RF components that can maintain performance across multiple frequency bands without the need for multiple discrete devices. Alongside this, the requirement for real-time adaptability in RF systems has introduced the concept of tunability. Devices need not only to function across various frequencies but also to dynamically alter their operational characteristics, such as the phase shift, gain, or bandwidth.

The convergence of broadband and tunable features within RF phase shifters is a crucial innovation that addresses contemporary challenges in communication and sensing. Broadband and tunable RF phase shifters offer the flexibility and scalability necessary to accommodate evolving standards and multifunctional platforms. By enabling dynamic phase adjustments across a wide spectrum, such phase shifters facilitate sophisticated operations like adaptive beam steering and interference mitigation.

Moreover, advancements in semiconductor and material technologies, including CMOS (Complementary Metal-Oxide-Semiconductor), GaN (Gallium Nitride), and MEMS (Microelectromechanical Systems), have significantly influenced the development of RF phase shifters. These innovations enable high-performance, compact, and energy-efficient designs, supporting the integration of phase shifters into portable and large-scale systems alike.

The development of broadband and tunable RF phase shifters is not merely an incremental improvement in RF technology. Rather, it represents a paradigm shift toward more intelligent, adaptable, and high-performance systems. These phase shifters have implications for the efficiency, coverage, and versatility of RF systems, impacting both consumer and defense applications. As such, the continued study and innovation in this field are crucial to staying ahead in the rapidly advancing world of wireless technology.

1.2 Key Terminologies

Understanding the core components of the thesis title requires a deep dive into the associated terminologies. Each term embodies a specific technological aspect that contributes to the overall objective of this research.

1.2.1 Radio Frequency (RF)

Radio Frequency (RF) refers to the range of electromagnetic frequencies from 3 kHz to 300 GHz. These frequencies are used in a wide array of applications including wireless communications, radar systems, navigation, and broadcasting. RF engineering deals with the design and application of devices that operate within this frequency range. The behavior of electrical signals at RF differs significantly from those at lower frequencies, necessitating specialized techniques in circuit design, signal processing, and electromagnetic compatibility.

In modern communication systems, RF technology enables wireless connectivity over various platforms, such as mobile phones, satellite links, Wi-Fi networks, and remote sensing devices. The increasing data rate requirements and spectrum scarcity have driven innovations in RF component design, aiming for better efficiency, linearity, and signal integrity.

RF systems must deal with issues such as signal attenuation, reflection, noise, and interference, all of which become more pronounced at higher frequencies. Techniques such as impedance matching, filtering, and shielding are crucial for effective RF design. Moreover, RF systems are increasingly integrated with digital technologies, leading to complex mixed-signal environments that further challenge traditional design methodologies.

1.2.2 Phase Shifter

A phase shifter is a device that alters the phase angle of an input signal while ideally maintaining its amplitude and frequency. It is a fundamental component in RF and microwave systems, particularly in phased-array antennas, where it allows for electronic beam steering without physical movement of antenna elements. Phase shifters can be analog or digital, fixed or variable, and passive or active, depending on the implementation and application.

In analog phase shifters, the phase shift is controlled continuously, often through varactors, resistive networks, or transmission line structures. Digital phase shifters, on the other hand, use switched delay lines or digital logic to introduce discrete phase changes. The performance of a phase shifter is characterized by metrics such as phase resolution, insertion loss, bandwidth, linearity, and power handling capability.

Phase shifters can be implemented using various technologies such as:

- **Ferrite phase shifters**, which are based on magnetic materials and are commonly used in military radar systems.

- **Liquid crystal phase shifters**, which are compact and useful in reconfigurable systems.

- **MEMS-based phase shifters**, offering low power consumption and high precision.

- **Semiconductor-based phase shifters**, especially those fabricated using CMOS or GaAs processes for integration with RFICs

Each technology comes with trade-offs in terms of speed, power, size, cost, and compatibility with other system components. The selection of an appropriate phase shifter depends heavily on the system requirements and operating environment.

1.2.3 Broadband

Broadband, in the context of RF engineering, refers to the capability of a device or system to operate over a wide range of frequencies. A broadband phase shifter can provide consistent performance, including a stable phase shift and low insertion loss, across a large frequency band. This is particularly valuable in systems where multi-band operation or frequency agility is required, such as in cognitive radios, military communications, and radar systems.

Designing broadband components presents unique challenges due to the frequency-dependent behavior of circuits and materials. Achieving wideband performance typically involves complex circuit topologies, wideband matching networks, and broadband impedance transformation techniques. Nevertheless, broadband capability enhances system flexibility, reduces the need for multiple devices, and simplifies hardware design.

In practical terms, broadband systems minimize the number of components required for multi-band support, reduce weight and size in integrated platforms, and improve cost efficiency. The increasing proliferation of multi-band devices in both commercial and defense sectors makes broadband RF components an area of ongoing research and innovation.

1.2.4 Tunable

Tunability refers to the ability of a device to adjust its operational characteristics in real time. A tunable RF phase shifter can vary its phase shift dynamically, allowing systems to adapt to changing environmental conditions, operational requirements, or signal paths. Tunability is essential in adaptive systems where fixed configurations cannot meet the demands of variable scenarios.

Technologies that enable tunability include voltage-controlled elements (such as varactors), microelectromechanical switches, magnetic materials, and ferroelectric devices. Tunable phase shifters support frequency hopping, agile beamforming, and dynamic spectrum access, which are increasingly important in congested and contested electromagnetic environments.

Moreover, tunable systems can mitigate hardware redundancy by using a single reconfigurable unit in place of multiple fixed-function devices. This not only saves space and power but also allows for software-defined control, enabling systems to be more intelligent and responsive.

1.3 Motivation

The motivation behind pursuing research in broadband and tunable RF phase shifters arises from the pressing demands of modern RF systems for adaptability, performance, and scalability. In traditional antenna systems, beam steering was achieved mechanically by rotating the antenna. This approach is inherently slow, prone to mechanical wear, and unsuitable for rapid reconfiguration. The development of electronically steerable arrays revolutionized the field, and at the core of this innovation lies the phase shifter.

Modern applications such as 5G/6G, advanced radar systems, and satellite communications demand highly agile, broadband, and reconfigurable components. These systems often operate over multiple bands and in diverse conditions, requiring phase shifters that not only function across a wide frequency range but also provide fine-grained, real-time tunability.

For example, in 5G networks, millimeter-wave communication involves beamforming to overcome high path loss. This beamforming is implemented through phased arrays where each antenna element requires a phase shifter. The quality of beam steering depends on the resolution, linearity, and bandwidth of the phase shifters. Similarly, in synthetic aperture radar (SAR) and multiple-input-multiple-output (MIMO) systems, tunable broadband phase shifters allow for enhanced image resolution and spatial multiplexing.

Furthermore, with the global move toward spectrum sharing and cognitive radio, devices must dynamically adapt to available spectrum. Phase shifters that support both tunability and broadband operation enable such adaptability, allowing for more efficient use of the RF spectrum.

Additionally, from a research and academic perspective, the design and optimization of RF phase shifters represent a challenging and enriching problem involving microwave theory, circuit design, electromagnetics, materials science, and signal processing. Innovations in this area not only contribute to academic knowledge but also have direct practical implications in defense, telecommunications, and space exploration.

In summary, the primary motivation for this research stems from:

- The increasing demand for agile and adaptive communication systems.
- The limitations of existing phase shifter technologies in terms of bandwidth and tunability.
- The potential to contribute to advanced applications such as phased-array antennas, radar, and reconfigurable wireless systems.
- The academic challenge and interdisciplinary nature of the problem, offering significant learning and contribution opportunities.

1.4 Evolution of Phase Shifters

1.4.1 Early RF Systems and Limitations

In the early stages of wireless communication and radar, systems were heavily dependent on analog and mechanical components. Phase shifting was achieved using mechanical rotary joints and waveguide sections. These components were bulky, slow, and unsuitable for frequency-agile applications.

1.4.2 Transition to Solid-State Technologies

The emergence of solid-state electronics, such as PIN diodes and varactors, allowed for compact, faster, and more reliable phase shifters. However, the trade-off was often increased insertion loss, limited bandwidth, and reduced tunability.

1.4.3 Integration with MMIC and RFIC

Advancements in MMIC (Monolithic Microwave Integrated Circuit) and RFIC (Radio Frequency Integrated Circuit) technologies allowed phase shifters to be fabricated using CMOS, GaAs, and GaN, enabling integration with amplifiers, mixers, and oscillators on a single chip.

1.4.4 MEMS and Digital Phase Shifters

The development of MEMS introduced extremely low-loss, high-linearity phase shifters with mechanical tuning elements on a microscopic scale. Digital phase shifters using switched delay lines brought high-speed operation and better repeatability.

1.5 Types of Phase Shifters

1.5.1 Analog vs Digital Phase Shifter

Analog: Offers continuous phase change. Used in systems requiring fine control.

Digital: Offers discrete phase steps, often in powers of two (e.g., 2-bit, 4-bit phase shifters).

Type	Pros	Cons
Analog	High resolution, continuous control	Sensitive to temperature, complex control
Digital	Fast, repeatable, easy to control	Limited resolution, quantization error

1.5.2 Passive vs Active Phase Shifters

- **Passive**: Utilize reactive components like inductors and capacitors. No power gain but lower noise.

- **Active**: Incorporate amplifying elements to compensate for loss but may introduce non-linearity.

1.6 Technologies for Broadband and Tunable Phase Shifters

1.6.1 CMOS and BiCMOS

Ideal for low-power, high-integration scenarios. Enables on-chip control logic and RF path in a compact footprint.

1.6.2 GaN and GaAs

Support high-frequency operation with superior power handling. Preferred for military and satellite applications.

1.6.3 Ferroelectric and Liquid Crystal Materials

Offer tunability through changes in dielectric properties. Widely used in reconfigurable antennas and tunable filters.

1.6.4 MEMS

Provide precision mechanical tuning. Trade-offs include slower response times and complex fabrication.

1.7 Mathematical Basis of Phase Shifting

1.7.1 Phase Angle and Signal Representation

A sinusoidal signal is given by:

$$v(t) = A\cos(\omega t + \phi)$$

Where ϕ is the phase angle. A phase shifter alters ϕ without changing amplitude or frequency.

1.7.2 Time Delay and Phase Shift

Phase shift $\Delta\phi$ due to a time delay τ is:

$$\Delta\phi = 2\pi f\tau$$

This highlights how tunable delay lines are fundamental to many phase shifter architectures.

1.7.3 Vector Modulation

Modern phase shifters sometimes use vector modulator techniques, combining in-phase (I) and quadrature (Q) components:

$$V_{\text{out}} = I\cos(\omega t) + Q\sin(\omega t)$$

Adjusting I and Q allows dynamic control over phase and amplitude.

1.8 Applications in Modern RF Systems

1.8.1 5G and 6G Wireless Networks

- Beamforming for mmWave communication.
- MIMO systems for spatial multiplexing.
- Dynamic spectrum allocation.

1.8.2 Radar and Defense Systems

- Synthetic Aperture Radar (SAR)
- Electronic Warfare (EW)
- Target tracking with adaptive beam steering

1.8.3 Satellite and Aerospace

- Space-based phased arrays
- Multi-beam satellite links
- Power-efficient reconfigurable RF payloads

1.8.4 IoT and Smart Infrastructure

- Adaptive RF links for sensor networks
- Interference mitigation in dense environments

1.9 Challenges in Design and Implementation

1.9.1 Trade-off Between Bandwidth and Phase Linearity

Wider bandwidth often comes at the cost of phase distortion. Ensuring consistent performance across bands is a key design challenge.

1.9.2 Integration with Antenna Arrays

Large-scale arrays require many phase shifters with minimal size and power per unit.

1.9.3 Control and Calibration

Maintaining calibration across temperature ranges, aging, and environmental changes is essential.

1.9.4 Insertion Loss and Power Efficiency

Especially critical for portable and space applications where every dB of loss matters.

Chapter 2: Literature Review

2.1 Introduction

The growing demand for high-speed, reconfigurable, and energy-efficient RF front-end systems in next-generation wireless communications (5G/6G), phased-array radars, and software-defined radios has intensified the development of broadband and tunable RF phase shifters. Traditional phase shifters often suffer from limitations such as narrow bandwidth, fixed phase states, or poor integration flexibility.

This chapter presents a comprehensive literature review of state-of-the-art techniques in RF phase shifting. We categorize and discuss the most relevant research in digital, analog, reconfigurable, and miniaturized phase shifter technologies. Specific attention is given to the bandwidth, tunability, design structure, and application feasibility of each method. Each section refers to and paraphrases from peer-reviewed research papers that are directly relevant to this thesis.

2.2 Digital Phase Shifters with Broadband Capability

2.2.1 Broadband Phase Shifter Using Phase-Slope Tuning

A novel broadband digital phase shifter based on microstrip-to-slotline transitions and microstrip-loaded slotline structures has been proposed in [1]. The key innovation in this paper lies in exploiting phase-slope tuning — where the phase response of a transition structure varies with frequency due to changes in impedance geometry.

The proposed unit cell combines a λ/4 microstrip slotline with a short-circuited loaded structure, creating controllable phase delays. By cascading these unit cells, a multi-bit architecture (up to 5 bits) was demonstrated, capable of achieving full 360° phase shift.

Performance:

- Bandwidth: 55%
- RMS phase error: <4.5°
- Insertion loss: ~2 dB per stage

This technique is suitable for beamforming arrays where compactness and digitally controlled reconfigurability are crucial. The design is also compatible with planar fabrication, easing integration in RFICs.

2.3 Continuously Tunable Phase Shifters with Filtering Functionality

2.3.1 Tunable Wideband Differential Phase Shifter with Passband Alignment

Zheng et al. [2] introduced a continuously tunable differential phase shifter that integrates phase shifting and bandpass filtering in one structure. The design uses a varactor-loaded transversal interference network to provide tunable capacitance and hence a variable phase response.

To address the issue of passband shift during tuning, the authors embedded shorted stubs that act as correctors, keeping the passband aligned across different tuning states. This structure is unique in offering simultaneous spectral selectivity and phase adaptability.

Performance:

- Phase tuning: 7°–127°
- Fractional bandwidth: >72%
- Alignment bandwidth: >95.9%

Such a dual-functional design is highly useful in software-defined radios, where both phase agility and spectrum filtering are needed for interference rejection.

2.4 Reconfigurable Phase Shifter Using SIW and PIN Diodes

2.4.1 SIW Phase Shifter with PIN Diode-Controlled Parallel Stubs

Louati et al. [3] designed a reconfigurable phase shifter based on Substrate Integrated Waveguide (SIW) technology. The phase shift is obtained by integrating surface-mount PIN diodes onto coplanar waveguide (CPW) stubs that are connected in parallel to the SIW main line.

When diodes are switched ON or OFF, the effective electrical length changes, which causes discrete phase shifts. The proposed design achieves

3 switching states, with a maximum phase shift of 60° and low loss across the 4.8–6 GHz band.

Performance:

- Phase range: Up to 60°
- Insertion loss: <1.5 dB
- Size: Compact single-layer PCB

This approach is well-suited for modular radar systems and low-cost phased arrays, due to its simplicity, reconfigurability, and planar structure.

2.5 Compact Filtering Phase Shifter with Simple Layout

2.5.1 Face-to-Face Coupled Microstrip Phase Shifter

Shi et al. [4] presented a compact phase shifter that also functions as a bandpass filter. The core of the design includes cascaded quarter-wave coupled lines and face-to-face microstrip feeds that inherently shape the frequency response.

This structure uses even- and odd-mode impedance engineering to produce distinct phase shifts (e.g., 45° and 90°) while achieving high return loss and low insertion loss.

Performance:

- Phase options: 45°, 90°

- Bandwidth: >57%
- Return loss: <–14 dB

Its simple structure and planar single-layer realization make it highly suitable for compact RF modules, especially where both filtering and phase control are desired.

2.6 Wideband 90° Filtering Phase Shifter Using Broadside-Coupled MSLs

2.6.1 Broadside-Coupled MSL Phase Shifter

Feng et al. [5] proposed a 90° phase shifter using broadside-coupled microstrip lines (MSLs), where coupling is achieved vertically (top-to-bottom layer), improving performance over conventional edge coupling.

The system includes a three-pole filtering structure for the main path and a reference path with consistent delay. The broadside configuration improves fabrication tolerance and coupling strength.

Performance:

- Phase shift: 90° ±5°
- Bandwidth: 80%
- Structure: Compact dual-layer MSL

Ideal for massive MIMO systems and high-density phased arrays, this design balances high performance with PCB manufacturability.

2.7 Miniaturized Phase Shifters Based on Multiple Resonators

2.7.1 Miniaturized Phase Shifter with Resonator Network

Yang et al. [6] developed a synthesis approach for phase shifters using multiple series and shunt resonators. The layout uses a closed-form design method, where the resonator lengths and spacings are derived based on desired phase shift and bandwidth.

The structure achieves >120% fractional bandwidth while minimizing area (up to 90% smaller than traditional designs).

Performance:

- Bandwidth: >120%
- Size: Ultra-compact
- Applications: Wearable RF, embedded antennas

Its design methodology is especially suited for portable communication devices where space and power are constrained.

2.8 Single-Layer Broadband Phase Shifter Using MMR and λ/4 Stubs

2.8.1 MMR and Shunt Stub Hybrid Design

Lyu et al. [7] introduced a phase shifter using a multimode resonator (MMR) and two short-circuited λ/4 stubs, achieving a single-layer layout with exceptional bandwidth and low phase distortion.

Using a synthesis method, the authors ensured that return loss and phase deviation remained within stringent limits across a large band.

Performance:

- Phase: 90° ±5°
- Bandwidth: 102%
- Insertion loss: <0.7 dB

Its single-layer nature makes it optimal for low-cost, scalable antenna arrays, with excellent potential for use in automotive radar and satellite terminals.

2.9 Comparative Analysis

Technique	Bandwidth	Tuning	Complexity	Application
Digital Phase-Slope	~55%	Discrete	Moderate	Phased arrays
Varactor-Based Analog	Wide	Continuous	Moderate	Cognitive radios
SIW + PIN Diodes	4.8–6 GHz	Discrete	Low	Radar, aerospace
Filtering PS (Compact)	~57%	Fixed	Low	IoT, mobile RF modules
Broadside MSL	~80%	Fixed	Low	MIMO arrays
Multi-Resonator Synthesized	>120%	Fixed	High	Embedded, wearable systems
MMR with Shunt Stubs	~100%	Fixed	Low	Scalable RF networks

2.10 Conclusion

The literature reveals a diversity of design philosophies in the pursuit of broadband and tunable RF phase shifters. From digitally reconfigurable devices to compact analog filters, each technique serves a niche depending on bandwidth, integration level, and required tunability.

For this thesis, insights from [1]–[7] will be leveraged in Chapter 3 to propose a design that optimizes performance across these dimensions, with a focus on wideband operation, continuous tuning, and system integration.

Chapter 3: Design and Implementation of 90° phase shifters

3.1 Overview

This chapter explains how to make, set up, and operate two different types of broadband RF phase shifters. We looked closely at the most recent breakthroughs in RF phase shifting technologies before making the designs. We looked at flat buildings that are simple to build, work well in a lot of different situations, and don't lose much. The designs are both built on single-layer substrates to save money and make it easier to fit them together. This chapter has simulations, explanations for the design, theoretical background, and information from other investigations. We also looked at a design that isn't like any of the ones that are already out there to see what its prospective merits and cons are.

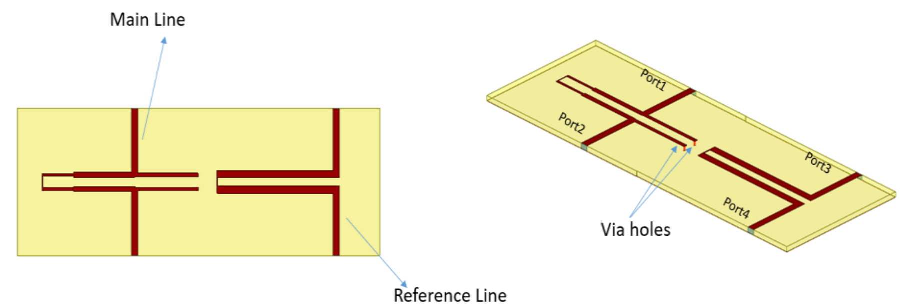
3.2 Design 1: A broadband phase shifter that uses weakly coupled microstrip lines

3.2.1 Design Motivation

The first concept employs a microstrip layout that doesn't link very well. The weakly linked lines in this configuration are what make the phase delay between the reference line and the main transmission line. This arrangement lets a single-layer PCB shift phases over a wide range without the need for vias or lumped components. This way of designing things saves money, cuts down on signal loss, and makes things easier to build. The structure also has a fractional bandwidth of more than 100%, a return loss of less than 22 dB, and an insertion loss of less than 0.5 dB. This is backed up by earlier studies and validated by our simulations.

This design is useful for beamforming, fixed-bit phase shift networks, and distributed antenna systems, where parts that are cheap, compact, and have low loss are particularly critical. This design is more stable than other tunable systems and performs better over a larger range of frequencies. It is also better at staying stable when it gets hot.

3.2.2 Theory, Structure, and How It Works



Structure of Phase Shifter Using Weakly Coupled Lines **Three-dimensional structure**

Fig.3.0

This phase shifter uses weak electromagnetic coupling to change the phase between two transmission lines. One path has a straight microstrip line, and the other way has a section that is only weakly connected. The signal that travels through the linked line is a little behind the signal that travels through the main line. This is because the energy moves along each path in a different way and spreads out.

There is a phase shift because the two pathways have different delays. You can very accurately regulate the amount of delay and the phase difference by modifying the length and spacing of the connected lines. A very crucial component of the design is to keep the connection weak. This enables the delay change slowly over a large range of frequencies, which is how a broadband phase shifter works.

The impedance changes because the lines' shapes change. You can change the phase response by adjusting the characteristic impedance and signal velocity of microstrip lines that are either broader or narrower. The design is passive, therefore it is always the same, steady, and trustworthy. This is useful for situations that happen a lot and need the phase behavior to stay the same over a large range of frequencies.

The lengths of the main and reference transmission lines set the phase shift, while the effective dielectric constant of the substrate sets the phase velocity. The phase delay is also affected by the difference in impedance between the linked and uncoupled lines.

Impedance has a lot to do with this. The impedance changes when the line widths change, which influences how fast signals move and how much the phase rotates over time. The length and space between the linked line segments affect how much and how smoothly the phase shift happens.

3.2.3 Results and Simulation

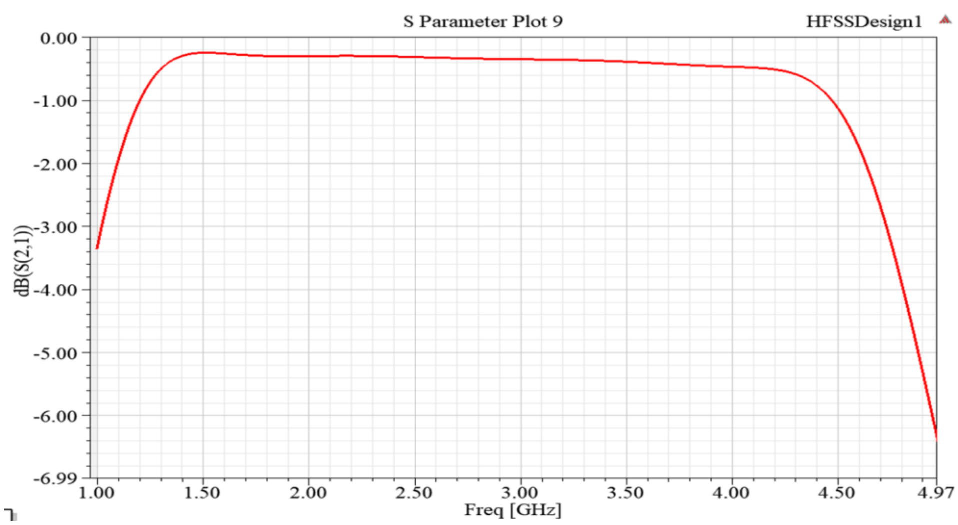


Fig.3.1

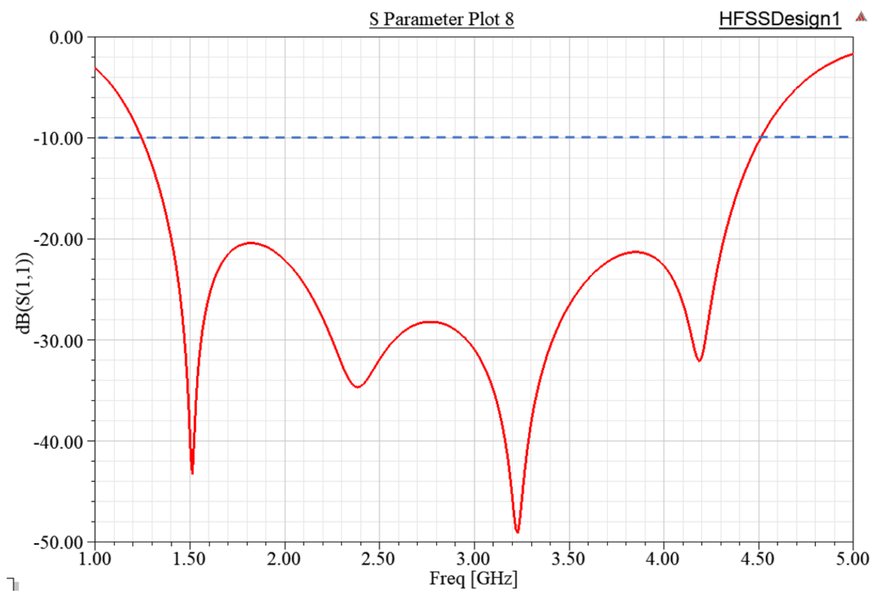


Fig.3.2

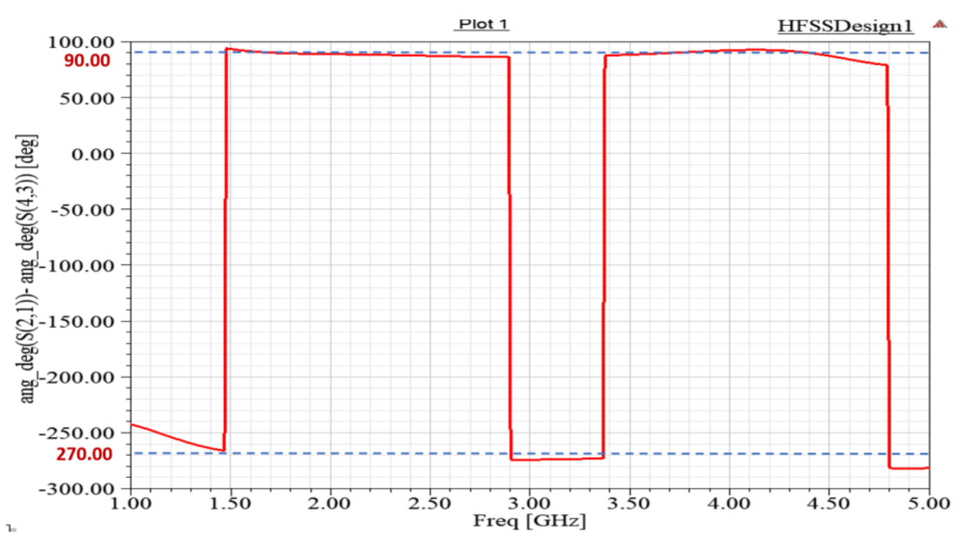


Fig.3.3

We utilized Ansys HFSS to make a model of the phase shifter. The Rogers RO4350B substrate has a dielectric constant of 3.48 and a thickness of 0.762 mm. It is a common material for RF applications since it doesn't lose much dielectric energy and stays stable at high temperatures. The simulation technique used fine meshing of the connected segments, adaptive frequency sweeps, and port calibration to check that the phase and S-parameter predictions were right.

The purpose of the design was to produce a phase shift of 90° ±6° between 1.49 GHz and 4.41 GHz. A parametric analysis of essential layout variables, such as the distance between coupled lines, the widths of the lines, and the lengths of the main and reference lines, was done to make this happen. This strategy helped us determine the optimal arrangement that would work well even if the parts were created in different ways.

We learned a lot about how well the phase shifter operated at different frequencies from the S-parameters. The S21 parameter, which is also called the transmission coefficient, informs you how much power the circuit transfers. A low insertion loss ensures that power moves swiftly and smoothly. The S11 parameter, or return loss, shows you how much of the signal is sent back. When the values are lower, the impedance matching is better. The differential phase plot reveals if the target phase shift maintains the same at all frequencies.

The results of the simulation indicated that the performance was stable. The insertion loss (S21) stayed below 0.5 dB and the return loss (S11) was better than -15 dB across the complete frequency spectrum. The most essential thing is that the differential phase shift was between 90° and 6°. This means that this design is great for adjusting RF phase over a large range.

The simulated S-parameters provide us a lot of information about how well the phase shifter operates in the RF spectrum. The S21 parameter in Figure 3.1 indicates that the insertion loss is always less than 0.5 dB. This suggests that the design doesn't do a good job of blocking signals; they can easily get through.

The S11 parameter in Figure 3.2 indicates the return loss. The results reveal that the return loss is always less than -15 dB, while in certain places it climbs above -30 dB. This means that the impedance is pretty near to what it should be, and there isn't much signal reflection.

Figure 3.3 demonstrates how the phase shift changes for the two different ways of sending data. For much of the operational frequency range, the phase difference stays near to 90°. The design can keep the phase shift stable as predicted since there are two stable flat bands at 1.49–3.0 GHz and 3.4–4.5 GHz.

The horizontal lines at 90° and -270° point to where you can see how stable the phase and periodicity are. This indicates that phase shifts don't change between frequency bands. The clear vertical lines on the phase plot illustrate that the coupled structure adds a predictable phase delay without making the signal worse.

This design is suitable for phased array and wideband beamforming applications that require to keep phase discrepancies steady over a wide range of frequencies to gain the greatest performance from the system.

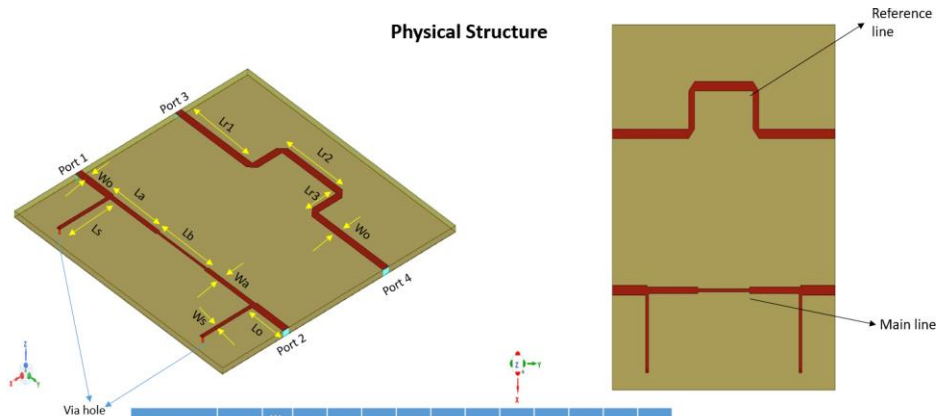
3.3 Design 2: A broadband phase shifter with multimode resonator and shunt λ/4 stubs

3.3.1 Design Motivation

This design was chosen because it has been shown to be able to work well over a wide range of frequencies with little effort. It has three quarter-wavelength (λ/4) short-circuited stubs in its multimode resonator structure. This means it has low insertion loss, a wide bandwidth, and is easy to make in a flat shape. These features, along with the fact that it can be made in one layer, make it great for cheap, small RF systems.

You can change the phase difference with little change in group delay by using multimode resonators and λ/4 shunt stubs. This is very helpful for systems that need to stay in sync and keep the phase steady. The layout also supports symmetric design, which makes sure that power and phase are spread out evenly. It is even more useful because it can be made on a well-known and widely available substrate like Rogers RO4003C.

3.3.2 Theory, Structure, and How It Works



Parameters	La	Wa	Lb	Wb	Ls	Ws	LD	D	L0	W0	Lr1	Lr2	Lr3
Dimension (mm)	14.8	1.2	15.7	0.6	16.4	0.9	0.5	0.5	10	1.8	23	17.5	7.3

Fig.3.4

The phase shifter is built on a Rogers RO4003C substrate that is 0.813 mm thick, has a dielectric constant (ε_r) of 3.55, and a loss tangent (tanδ) of 0.0027. These features help keep the signal strong over a wide range of frequencies and cut down on dielectric losses. It is also designed to stay symmetrical to avoid common-mode imbalance, and it is tuned to work best around a center frequency of 3 GHz.

There is a folded main transmission line and a straight reference line in the layout. There are also three λ/4 short-circuited stubs on the main path. The structure has four ports: two for input (Port 1 and Port 3) and two for output (Port 2 and Port 4). The transmission line's dimensions are La = 14.8 mm, Lb = 15.7 mm, and Lr3 = 7.3 mm. All of these were improved through simulation. This arrangement takes up the least amount of space on the circuit while still giving the necessary 90° phase shift. Figure 3.4 shows the phase shifter's geometric layout from both a 3D and a top view.

The multimode resonator and three short-circuited λ/4 stubs work together to make this design's broadband phase shift possible. These pieces are put in the main transmission line to change the phase velocity that works. This adds the right amount of phase delay without making the signal worse. The multimode resonator can support more than one resonant frequency, which lets you change the phase transition properties. When the electromagnetic wave passes through this resonator, it excites several modes that interact with each other in a way that changes the phase response over a wide range of frequencies.

Each short-circuited λ/4 stub works as a part that chooses frequencies. At some resonance points, these stubs make the signal phase change quickly. But you can smooth out these changes by carefully matching the impedance and tuning the geometry. The stubs act as shunt loads to stop reflections and make the electrical length of the main path longer. The stubs and the multimode resonator work together to slow down the wavefront compared to the reference line. This gives the 90° phase shift that is needed.

Choosing the right characteristic impedances for each part of the phase shifter is an important step in making sure it works well over a wide range of frequencies. The quality of the transmission and the amount of phase delay are both affected by the impedance of the main line, stubs, and resonator arms. When things don't match up, there can be more reflection and a worse return loss, which makes the phase shift flatness worse. So, you need to optimize each transmission segment to find the best balance between size, bandwidth, and insertion loss.

The line's length and width are both important. For example, the guided wavelength on the chosen substrate at the center frequency sets the λ/4 stub length, and the width changes the impedance and reactance profile. Narrow lines have a higher impedance, which is good for making the phase delay longer. Wider lines have less impedance, which is good for matching or feeding sections. Getting these shapes and how they work with resonator modes just right makes sure that the broadband 90° phase shift happens with as little distortion as possible.

This design also doesn't let the phase jump suddenly because the resonator's behavior is always changing. For changing the group delay across the frequency band, the resonator's distributed inductance and capacitance are very important. The net phase shift is caused by the difference in delay between the main and reference lines. The length of the lines, the loaded stubs, and the modal behavior of the resonator all affect this delay.

This theoretical approach makes it possible to make a small, passive, and broadband solution that can be easily added to RF front-ends. It is stable because it doesn't have any moving parts, and the layout is easy to work with using traditional PCB fabrication methods. This is why it's good for phased-array, beamforming, and delay equalization systems in the real world.

The second phase shifter is a very small and effective way to get broadband 90° phase shifts. It can be used in phased array systems, beamforming networks, and delay equalization systems where phase accuracy and consistency are very important.

3.3.4 Results and Simulations

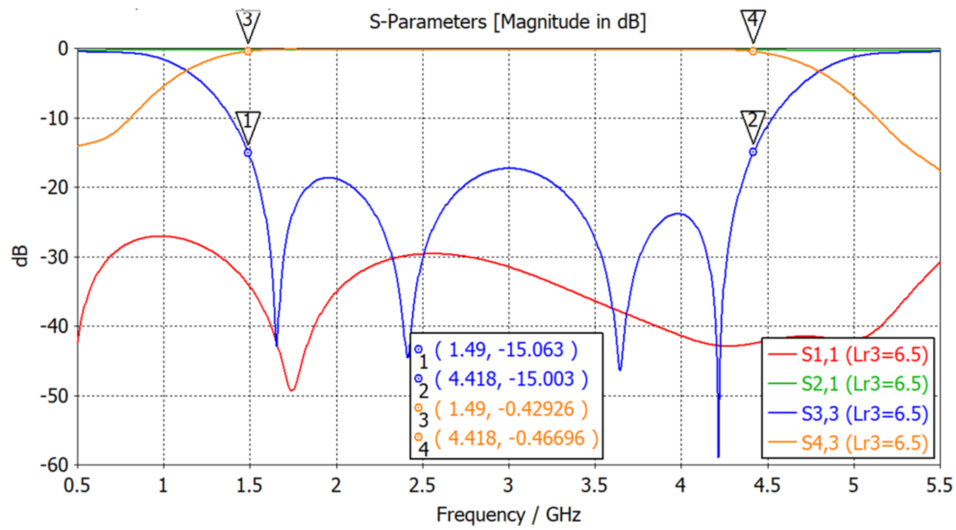


Fig.3.5

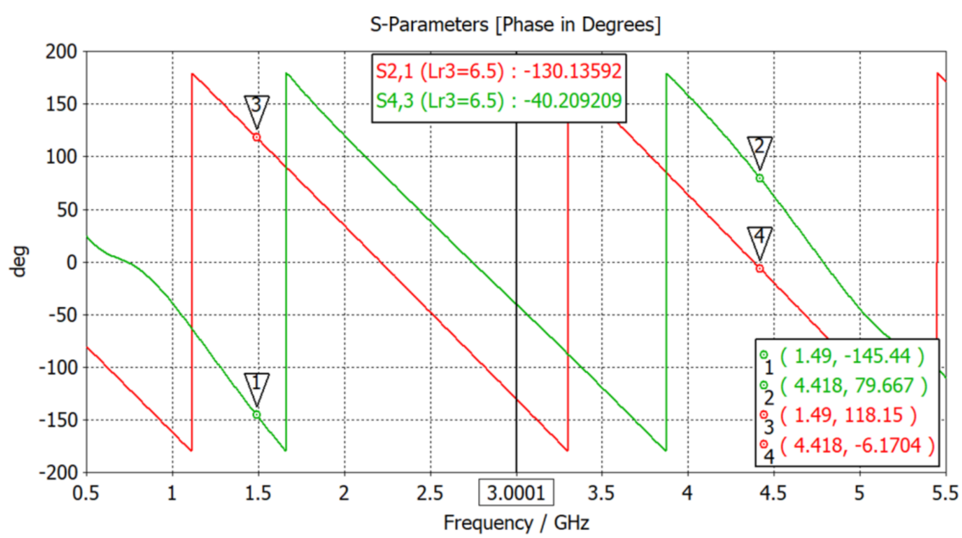


Fig.3.6

The simulated S-parameters are shown in Figure 3.5. The S21 (green) and S43 (orange) values tell us how well the main and reference lines send signals. Both paths show almost 0 dB transmission across the desired frequency band, which means that the signal is being sent quickly. S11 (red) and S33 (blue) show the return loss. It goes below -40 dB at important resonant frequencies like 1.49 GHz and 4.42 GHz. These deep nulls mean that the impedance matching is better and the signal reflection is lower.

Figure 3.6 shows how the S21 and S43 parameters change with different phases. The red curve shows the phase shift along the main line, and the green curve shows the reference line. The design works because it always has a phase difference of about 90° at a few frequencies, especially 1.49 GHz and 4.42 GHz. The phase progression is almost straight, which means that the group delay doesn't change much. This design is good for broadband use.

The second phase shifter is a small and very effective way to get 90° phase shifts in broadband. It can be used in phased array systems, beamforming networks, and delay equalization systems where phase accuracy and consistency are very important.

The simulated S-parameters are shown in Figure 3.5. The S21 (green) and S43 (orange) values tell us how well the main and reference lines send signals. Both paths show almost 0 dB transmission across the desired frequency band, which means that the signal is being sent quickly. S11 (red) and S33 (blue) show the return loss. It goes below -40 dB at important resonant frequencies like 1.49 GHz and 4.42 GHz. These deep nulls mean that the impedance matching is better and the signal reflection is lower.

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3.4 Summary

In this chapter, two designs for broadband RF phase shifters are suggested, analyzed, and tested using simulation. The first design used microstrip lines that weren't very strongly connected to each other to work in the ultra-wideband range. It had good phase shift linearity and was small. Using it showed how important line length and coupling strength are for changing the phase response.

The second design had both multimode resonators and λ/4 short-circuited stubs. This method worked well across a wide range of frequencies, giving a symmetric, broadband 90° phase shift with low insertion loss and high return loss. There were long explanations of how stub tuning, resonator modal behavior, and impedance control all work together to change the phase. The project was more useful because it used Rogers RO4003C substrate, which had low dielectric loss.

Both designs show how important planar, passive, and broadband phase-shifting solutions are becoming in next-generation RF systems. Their successful simulation and analysis set the stage for future experimental validation and integration into real-world communication hardware.

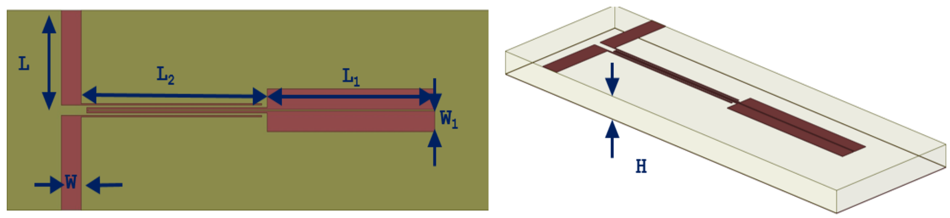
Chapter 4: Design and Analysis of Compact Filtering Phase Shifter

4.0 Reference Structure

Before looking at the 45° and 90° phase-shifted designs, you should look at the reference structure that is the main transmission line for measuring phase shifts. The Rogers RO4003C substrate used to make the reference structure has a thickness (h) of 0.813 mm, a relative permittivity (εr) of 3.55, and a loss tangent (tanδ) of 0.0027. It has a straight microstrip transmission line with no extra stubs or tuning elements. This keeps the phase delay to a minimum and gives us a baseline to compare to.

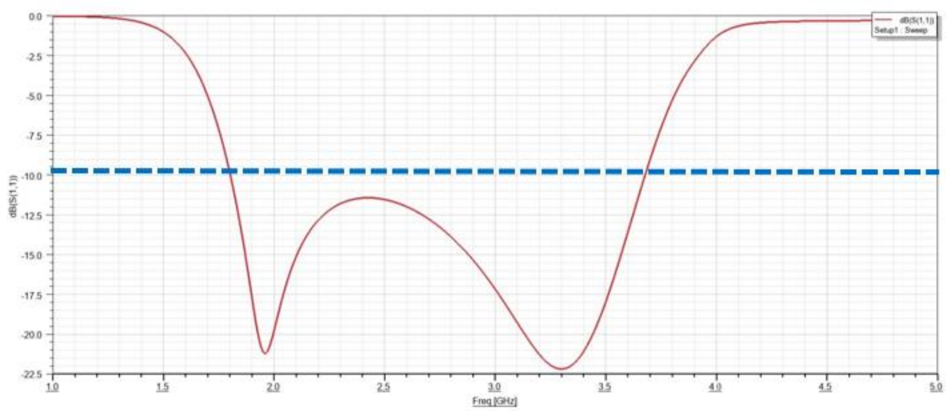
This line of reference is supposed to show what a zero phase shift looks like. You can find out the measured phase shift of changed structures by comparing the output signal phase to the reference signal phase. The line gets almost perfect impedance matching (around 50 ohms) because it is so simple. It also has a return loss (|S11|) below -15 dB over a wide bandwidth, which means that there is very little signal reflection. The insertion loss (|S21|) stays close to 0 dB, which means that the signal is being sent well. We can use this structure to reliably see how new design features, such as open-circuited stubs or impedance changes, affect the next phase-shifter configurations.

The reference structure is 1.85 mm wide, 7 mm long, 0 mm wide, 0 mm long, 0.7 mm wide, 15.5 mm long, 0.16 mm wide, 16.7 mm long, and 0.08 mm wide. The Rogers RO4003C substrate is 0.813 mm thick, has a dielectric constant of 3.55, and a loss tangent of 0.0027.



Design : Top View

Fig.4.0



S-Parameter

Fig.4.1

4.1 Design of 45° Compact Filtering Phase Shifter

4.1.1 Design Motivation

We chose the 45° compact filtering phase shifter because it can change the phase in a controlled way and filter out certain frequencies in a small space. A lot of RF systems, especially those that use phased arrays and beamforming networks, can use phase shifters that can give reliable phase offsets without needing extra filters. This design is very efficient in terms of size, cost, and signal quality because it can do two things at once. The layout is also symmetrical, which helps keep the performance stable and limits interference and cross-coupling between different parts.

4.1.2 Structure

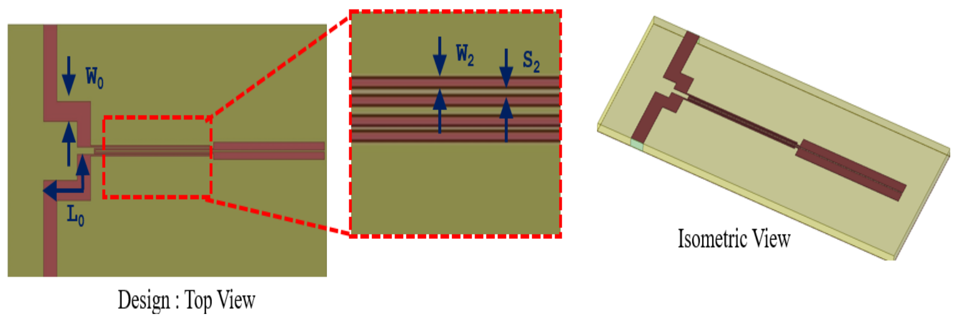


Fig.4.2

The Rogers RO4003C substrate that the 45° phase shifter is built on is 0.813 mm thick, has a dielectric constant of εr = 3.55, and a loss tangent of tanδ = 0.0027. The structure has a split path configuration that you can see from above. The reference line is one arm, and the delay line is the other. There are three open-circuited stubs and a lot of segments in the delay line that change the impedance. The larger inset shows the closely spaced coupled lines, which make the phase delay and bandwidth better.

The final sizes are W = 1.85 mm, L = 7 mm, W0 = 1.85 mm, L0 = 3.05 mm, W1 = 1.42 mm, L1 = 15.5 mm, W2 = 0.18 mm, L2 = 16.7 mm, and S2 = 0.12 mm.

4.1.3 Theory and Working Principle

The 45° compact phase shifter makes impedance discontinuities by using guided-wave propagation and stubs and stepped-width lines. The phase shift happens because the reference and delayed paths have different electrical lengths. Open-circuited stubs are frequency-selective parts that change the effective electrical length, which changes the phase. These stubs add capacitive and inductive reactance based on how often the input signal changes.

The coupled microstrip sections in the delay line also allow slow-wave propagation, which means that the phase delay per unit length is greater. The delay line is supposed to cause constructive and destructive interference with the reference path, which makes the phase difference that is needed. The parts, like the widths and spaces between the lines, all work together to get the characteristic impedance and electrical length just right. By making these parts as good as they can be, a target phase shift of 45° is reached over a wide range of frequencies while keeping reflection low and loss to a minimum.

This design is also small and allows for a high integration density in microwave circuits, which means that separate filtering parts are no longer needed. In general, it combines filtering and phase shifting into one layer, which makes things work better and takes up less space.

4.1.4 Parametric Analysis

We did a parametric sweep to find out how each design parameter, especially the stub width (W2), changed the result. We saw the return loss |S11| at different W2 values, which were between 0.17 mm and 0.24 mm. The plot shows that W2 = 0.18 mm had the best bandwidth and the least reflection. The return loss is now well below -15 dB from 1.77 GHz to 3.77 GHz, which means that the broadband is matching. The bandwidth is at its highest and the overall insertion loss is at its lowest. This shows that W2 = 0.18 mm is the best choice for wideband phase shift.

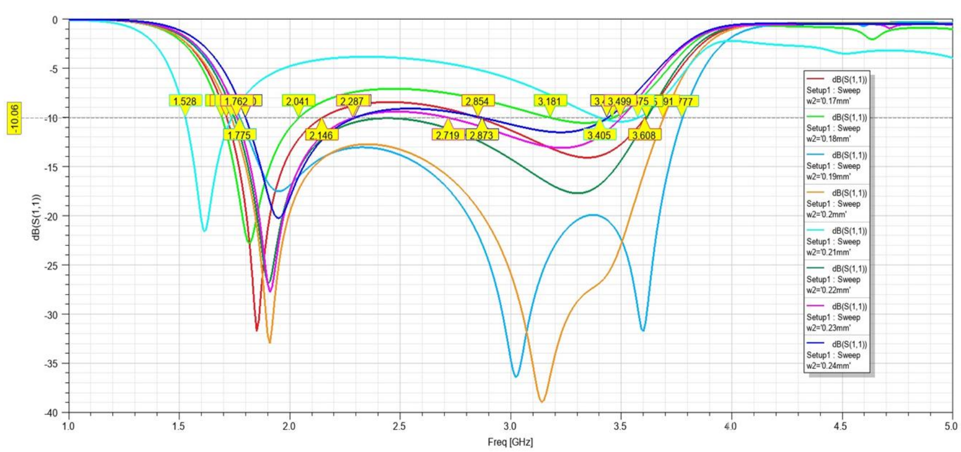


Fig.4.3

4.1.5 Results and Simulations

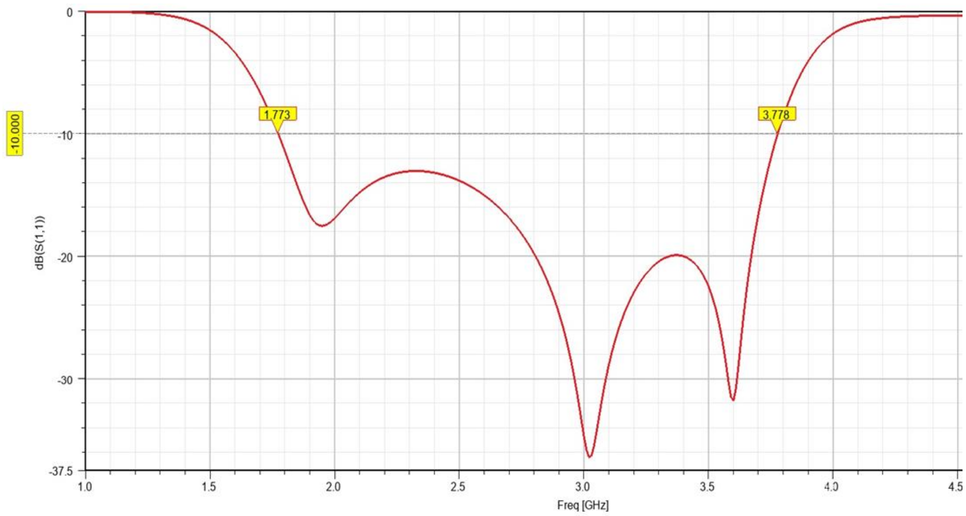


Fig.4.4

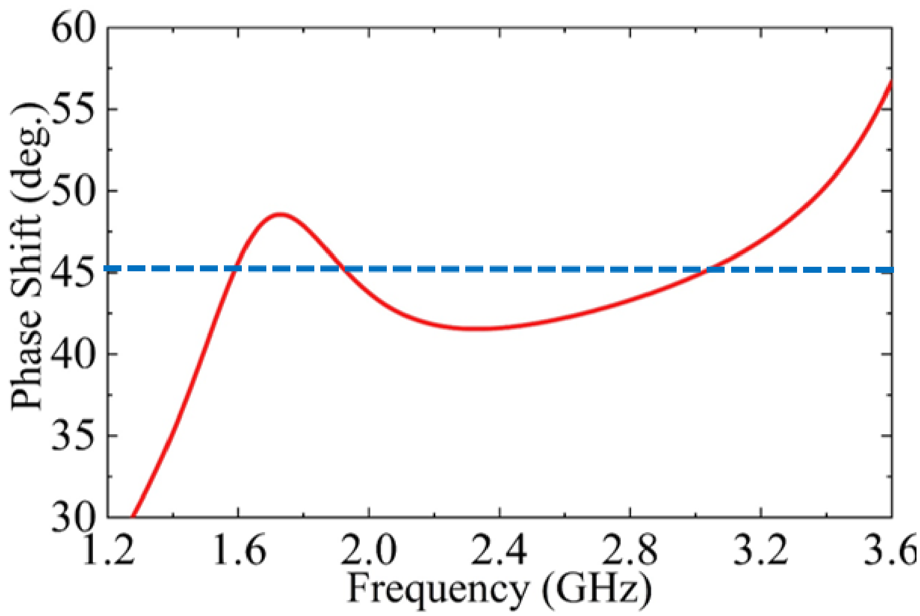


Fig.4.5

We used full-wave electromagnetic simulation to see how well the 45° compact filtering phase shifter worked. We looked at the important S-parameters, |S11| and |S21|, as well as the phase difference between the delayed and reference paths, from 1.0 GHz to 4.0 GHz.

The simulated return loss (|S11|) was always less than -10 dB in the frequency range of 1.77 GHz to 3.77 GHz. There was very little signal reflection because the impedance was perfectly matched. The S11 plot showed several resonance dips, which is interesting because they match how the open-circuited stubs in the delay line resonate. These dips improve the design's filtering ability by effectively blocking out unwanted frequency components by adding transmission zeros at certain frequencies.

The transmission coefficient (|S21|) was also good. The insertion loss stayed close to 0 dB in the same frequency band, which means that the device was able to send signals well. The structure has very little loss, which shows that the design works to keep the signal strength while adding the phase shift that is needed.

We found the phase shift response by looking at the difference between the phase of the signal that went through the delay path and the phase of the reference line. The simulation showed that the phase difference was stable and under control, with the curve staying close to 45° in the middle of the band of interest. The phase shift was between 40° and 48° between 1.6 GHz and 3.2 GHz. This shows that the design can give the desired shift with only a small change in frequency.

The results of these simulations show that the structure that was designed not only meets the phase shift requirement, but it also works well across a wide range of frequencies, reflects very little, and transmits very efficiently. It has a built-in filtering action, takes up little space, and is easy to make. Because of these things, it works well in broadband and multiband communication systems, beamforming networks, and RF front-ends that can be changed.

4.2 Design of 90° Compact Filtering Phase Shifter

4.2.1 Why This Design Was Chosen

The 90° compact filtering phase shifter is great for IQ modulators, phase array antennas, and image-rejection mixers because they need very precise quadrature phase relationships. With a longer phase delay, you can steer beams at bigger angles and get clearer signals. This design works well for both phase shifting and bandpass filtering in a small microstrip layout. This makes it easier to put everything together and makes the whole system easier to understand.

4.2.2 Structure

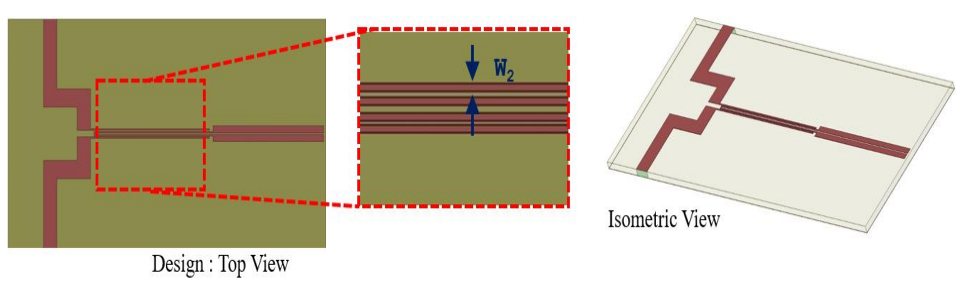


Fig.4.6

The Rogers RO4003C substrate is used to make the 90° phase shifter. There is a reference line and a delay line in the structure. There are three open-circuit stubs and stepped impedance sections in the delay line. These parts add controlled breaks and reactive elements that make the electrical length longer. This makes the shift in phase bigger.

4.2.3 Theory and Working Principle

The 90° compact phase shifter uses techniques from distributed transmission lines to filter and control phase delay. The stepped-impedance parts speed up phase velocity by acting like things that slow down waves. Open-circuited stubs, which are resonant parts, only make the phase delay longer. Putting these things together changes the phase by about 90° over a wide range of frequencies.

The signal changes the impedance as it goes through the delay path by interacting with the different stubs. The group delay has changed now. The physical and electrical lengths of the delay line are set so that the center frequency shifts by a quarter wavelength (λ/4). The angle goes from 90 degrees to 90 degrees. The stubs also get rid of signals that aren't in the right band, so the phase shifter can work as both a filter and a delay unit.

It is very useful for modern RF applications because it is small and can do two things at once. The design makes sure that the transmission works well over a wide range of frequencies, has very little phase ripple, and is very efficient.

4.2.4 Parametric Analysis

We changed the width (W2) and length (L0) of the stub and did a parametric sweep to see how the return loss changed. The study found that the best results came from L0 being 6.55 mm, S2 being 0.08 mm, W1 being 0.6 mm, and W2 being 0.15 mm. With these numbers, it was possible to match the impedance of broadband and get low reflection between 1.69 GHz and 3.78 GHz.

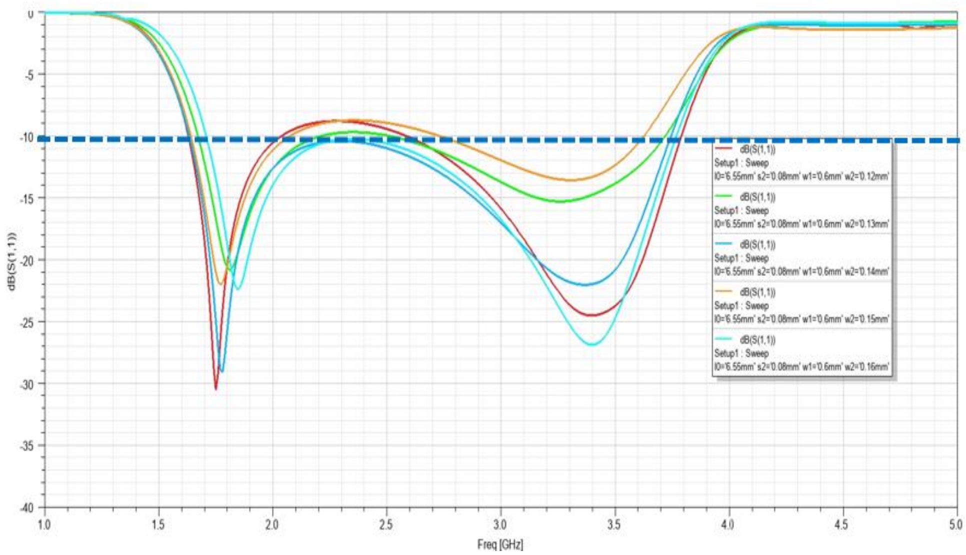


Fig.4.7

4.2.5 Results and Simulations

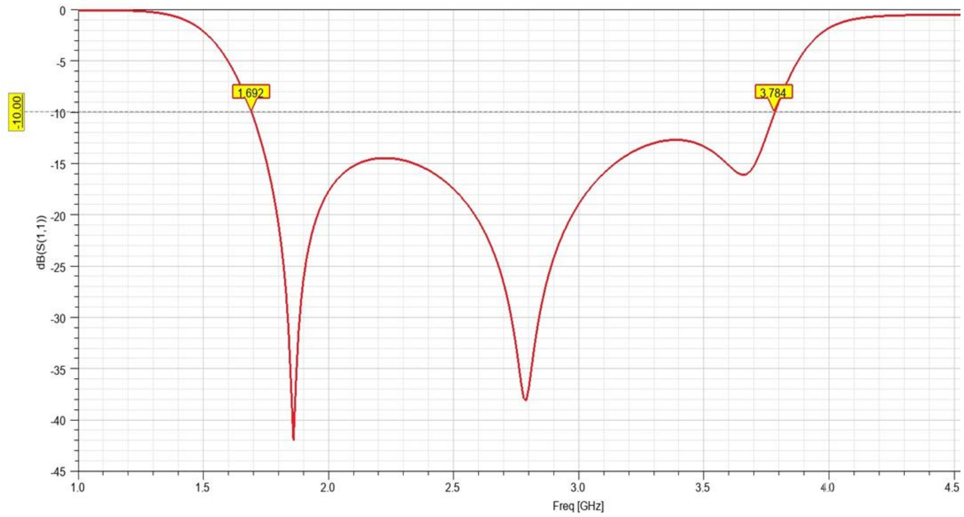


Fig.4.8

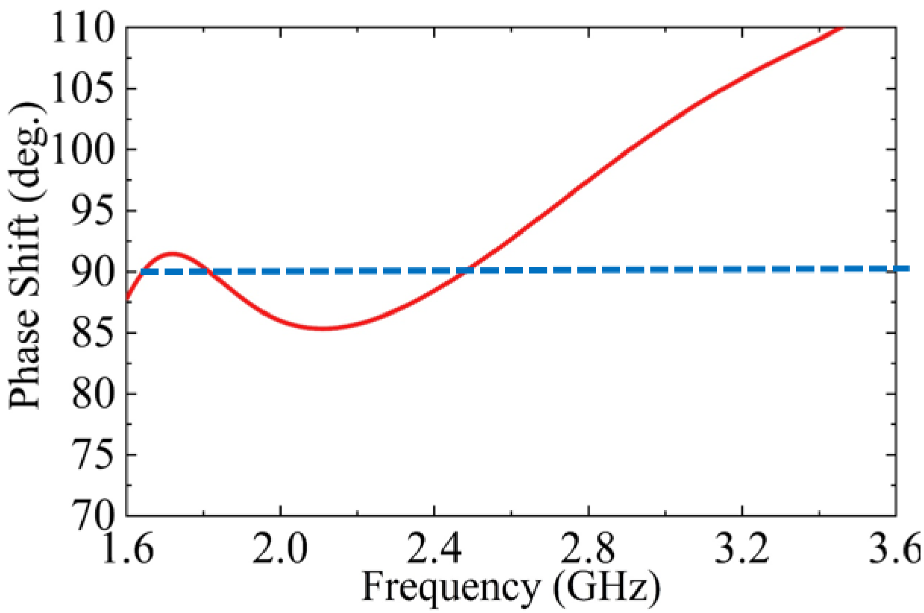


Fig.4.9

The return loss (|S11|) stays below -10 dB in the frequency range of 1.69 GHz to 3.78 GHz. This means that the impedance is a good match. The stubs add resonances to the S11 curve, which makes the filtering even better and gives it deep notches. This behavior shows that the structure doesn't reflect the signal very much and absorbs it well. This is very important for making sure that the signal stays strong in RF systems.

The transmission coefficient (|S21|) stays close to 0 dB for all the frequencies it can work with. This means that the signal is sent very quickly and with very little loss of quality. The |S21| response doesn't have any big drops in the wideband. This means that the shape of the design keeps a lot of energy inside and makes a strong link between the input and output ports. This means that the design is great for things that need to work well at a lot of different frequencies.

The phase shift plot shows that the phase response is 90° off at both 1.69 GHz and 3.78 GHz. In the middle of the band, the response stays pretty much the same. This is very helpful when you need steady quadrature signals for modulation or beamforming. The phase shift is flat and doesn't change much across a wide range of frequencies. This shows that both the resonant stub and the stepped impedance methods work.

You can change the characteristic impedance of stepped-impedance transmission lines. This makes the signal take longer to spread out, which adds to the delay. These features, along with open-circuited stubs that are tuned to certain resonant frequencies, make a composite structure that balances size, phase control, and frequency selectivity.

This structure can be used in phased array antenna systems, which need very precise 90° phase differences to change the direction of the beam or get rid of interference. It works with a lot of different frequencies and doesn't lose much signal when you plug it in. This is why it's good for new communication systems like 5G and radar.

4.3 Summary

In short, this chapter showed how to make, test, and rate the performance of small filtering phase shifters that can change the phase by 45° or 90°. The Rogers RO4003C substrate made sure that the dielectric worked the same way at all frequencies and that there wasn't much loss. We looked at a reference transmission line first to see how to measure the phase shift that the proposed designs would cause.

Using sections and stubs that change impedance and are open-circuited, the 45° phase shifter showed how to make a controlled phase delay without losing filtering power. Through parametric analysis and simulation, the design got a wide matching bandwidth of 1.77–3.77 GHz, a return loss of less than -10 dB, and a steady phase shift of about 45°.

The 90° phase shifter had better resonant properties and longer electrical length, which made the phase offset bigger. In the 1.69–3.78 GHz range, it had a low-reflection response and a stable phase shift that stayed between 85° and 110°, with 90° being the middle point. Adding stepped impedance sections and changing the size of the stubs made the filtering strong and the transmission fast.

These designs show that small phase shifters might be able to work in RF systems today. They can change the phase and filter at the same time. This makes circuits smaller, easier to put together, and with fewer parts. You can use them in communication front-ends, signal processing modules, and antenna arrays because they work so well and are made the way they are.

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