1
Introduction

1.1 BACKGROUND

The rapid evolution of wireless communication standards, particularly with the advent of 5G, has necessitated the development of advanced components capable of supporting the transmission of high data rate signals. 5G communication is expected to dramatically enhance the utilization of wireless services by providing improved data rates and wide bandwidth capabilities. The stringent requirements of 5G, especially in terms of accommodating the FR-2 band (28 GHz and above), have intensified the need for compact, planar components with low-loss transmission characteristics. The shift toward higher frequency bands accentuates the demand for innovative planar guiding media, such as the integration of various transmission lines, which is essential for augmenting system functionality. The integration of transmission lines is vital for meeting the demands of high-speed, high-capacity communication, which is crucial for the advancement of wideband microwave and millimeter-wave components. However, challenges such as substrate loss, ohmic loss, and radiation loss become more pronounced at higher frequencies, requiring meticulous design strategies to mitigate these losses. Furthermore, the widespread use of communication services drives the necessity for designing RF front-end systems with a compact form factor [Shao *et al.*, 2017a]. In recent years, researchers have focused on implementing Ku-band circuits and systems for satellite and RADAR communication. The Ku-band imposes rigorous requirements related to insertion loss, size, and design flexibility. While traditionally used in satellite and RADAR applications, Ku-band frequencies are now being explored for 5G, 6G, FR3, and non-terrestrial network (NTN) applications, owing to their potential for supporting high data rates and their compatibility with compact system designs. Currently, researchers are focusing on the development of high-performance RF front-end systems for mobile satellite reception within these frequency bands, leveraging the benefits of shorter wavelengths and broad bandwidth availability. To achieve this, such systems must be designed to integrate active circuits with passive components on a single board, ensuring a compact and efficient form factor that meets the requirements of modern mobile communication technologies

Moreover, designing active circuits for RF front-end systems in the millimeter-wave band for modern cellular phones presents a complex challenge, necessitating a careful balance between performance, power efficiency, and integration. Progress in planar technologies, innovative design methodologies, and advanced integration techniques are critical for meeting these rigorous system requirements and enabling their effective deployment in next-generation communication networks.

1.2 OVERVIEW OF EXISTING ACTIVE CIRCUITS FOR MODERN RF FRONT END SYSTEMS

Modern RF front-end systems are essential components in wireless communication devices, facilitating the transmission and reception of RF signals. These systems incorporate various active

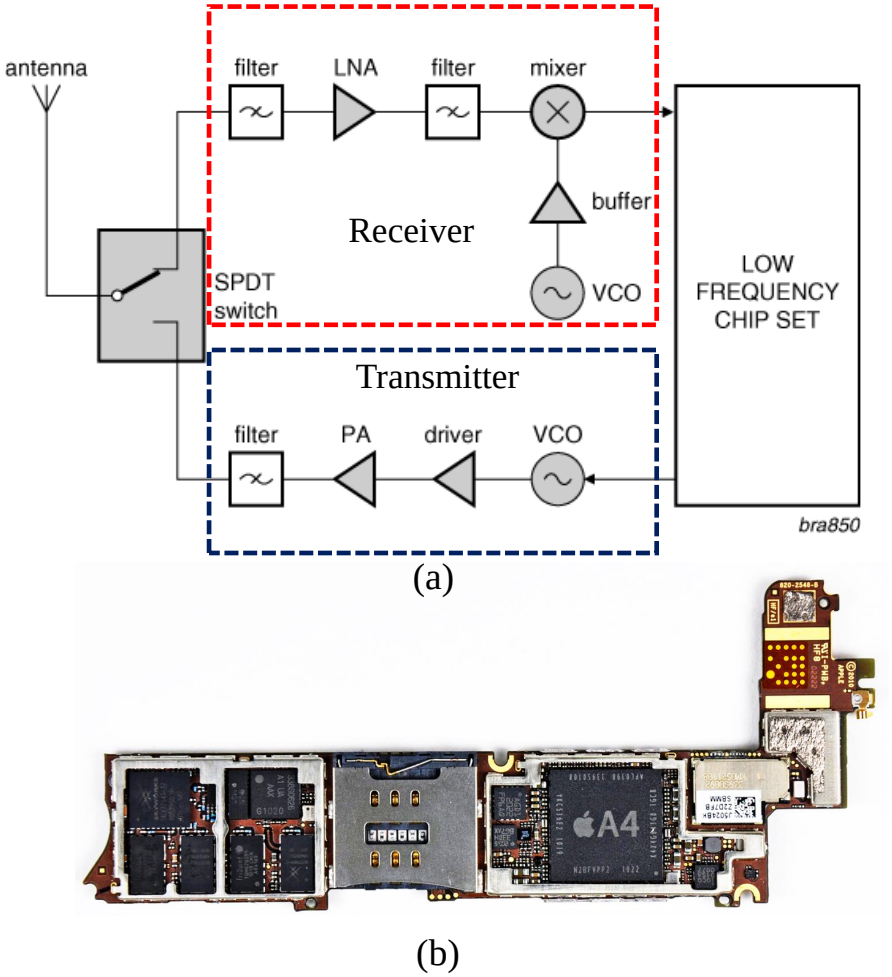


Figure 1.1 : (a)Block diagram of RF front End Modules Hamid and Alam [2019];(b) RF front-end modules (FEMs) in the Apple iPhone 4. [iFixit, 2010].

circuits to optimize performance, minimize power consumption, and accommodate the growing demand for higher data rates and broader bandwidths. As depicted in Figure 1.1(a), the functional components of these systems include both receiver and transmitter sections. The receiver section (Rx) comprises a filter, low-noise amplifier (LNA), mixer, and oscillator, while the transmitter section (Rx) consists of a power amplifier (PA), filter, and oscillator. Both sections utilize a common antenna via an SPDT (single-pole double-throw) switch. The Tx and Rx sections interface with a low-frequency chipset for basedband signal processing.

In Figure 1.1(b), multiple RF front-end modules (FEMs) tailored to various communication standards are illustrated within an Apple iPhone 4. As wireless services continue to evolve rapidly, modern cellular phones require distinct RF front-end components to support diverse communication protocols. The specific functionalities and design considerations of these components are discussed in detail below.

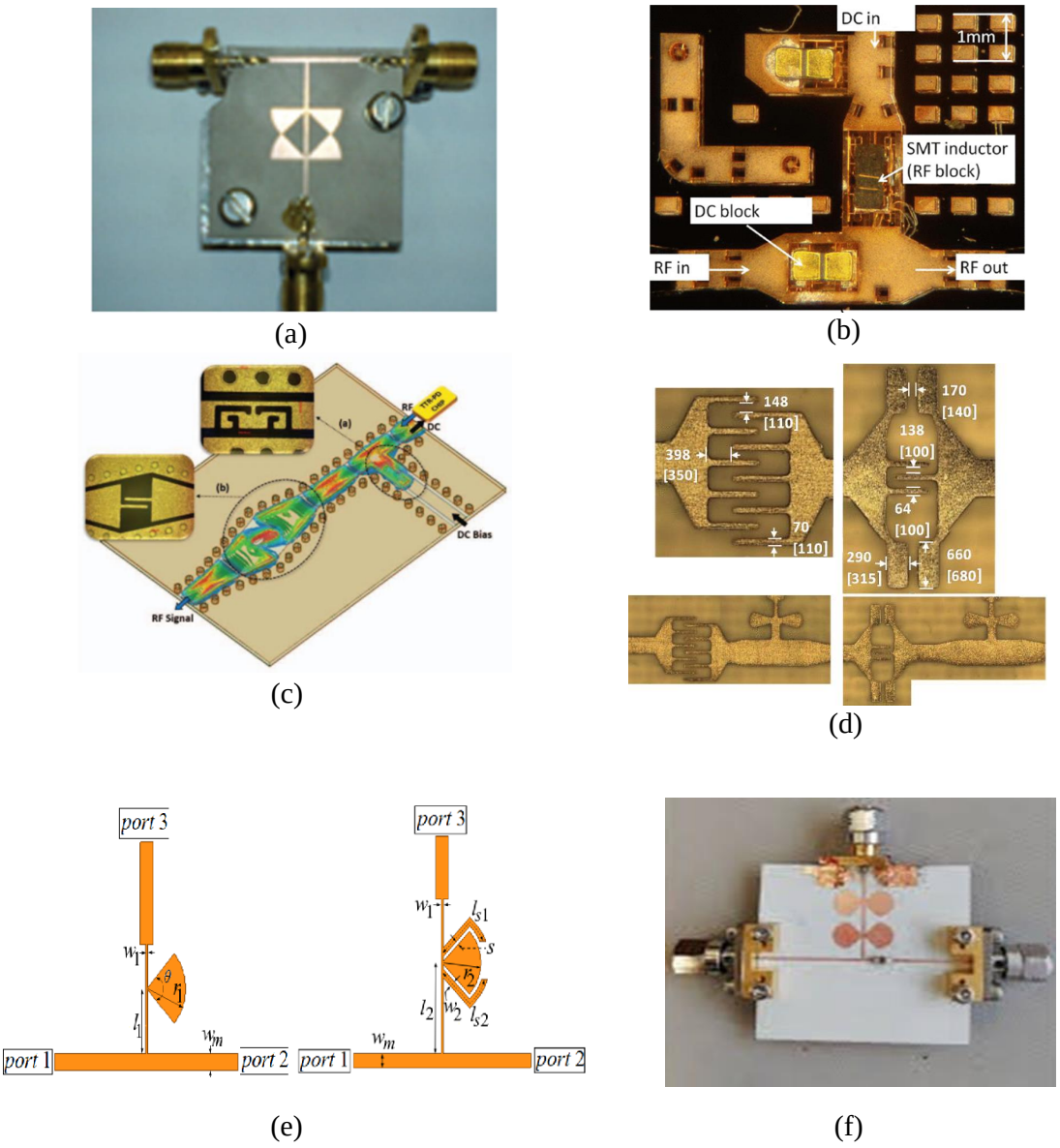


Figure 1.2 : (a) A novel broad-band microstrip radial stub resonator used in bias-T application [Dehbashi *et al.*, 2006];(b) Miniature bias-tee networks integrated in micro-coaxial lines[Cullens *et al.*, 2010b];(c) Compact E-Band (71-86 GHz) bias-tee module for external biasing of millimeter wave photodiodes[Khani *et al.*, 2015b];(d) Design of DC-Blocks and Bias-Tee on PCB for V-Band[Umar *et al.*, 2021a]; (e) An Improved Design of A Bias Tee Using A Modified Radial Stub [Jana *et al.*, 2019a]; (f) A double mirror stub design of broadband planar bias tee for system on chip integration [Yadav *et al.*, 2022]

1.2.1 Bias tee network

A bias tee network plays a vital role in integrating DC power and RF signals in active circuits, including amplifiers, mixers, oscillators, and switching circuits, while ensuring that these

signals do not interfere with each other. Active circuits require a DC bias for operation while simultaneously processing high-frequency RF signals. Recent advancements in broadband bias tee designs have centered on enhancing the frequency range, minimizing insertion loss, and improving overall performance across various applications. Figure 1.2(a) illustrates the design of a bias tee circuit that incorporates inclined-radial butterfly stubs joined at their points to introduce a compact broadband resonator. This configuration enhances the scattering parameters compared to conventional band-stop resonators, reducing the size of the band-stop resonator by approximately 50% relative to traditional two-stub designs [Dehbashi *et al.*, 2006]. Despite these improvements, the bandwidth of this bias tee remains limited due to the microstrip's semi-open structure, which is prone to radiation loss at higher frequencies. Figure 1.2(b) presents a broadband bias tee design compatible with micro-coaxial environments, fabricated using the PolyStrata™ process [Cullens *et al.*, 2010b]. Although this approach offers high performance, the fabrication process is costly. In Figure 1.2(c), the design features a planar RF choke centered around two slotted split-ring resonators (SRRs) integrated within the DC bias line to prevent RF signal leakage into the DC circuitry. The results from the DC-block section indicate that within the 71–76 GHz frequency range, the return loss (RL) exceeds 11 dB, the insertion loss (IL) remains below 2.2 dB, and isolation surpasses 30 dB. However, this bias tee design requires an expensive and specialized printed circuit board (PCB) fabrication technique with a 0.09 mm design resolution [Khani *et al.*, 2015b]. Figure 1.2(d) depicts an RF choke design that integrates a bow-tie stub with both DC blocks, forming two distinct bias-tee structures. The multi-finger bias tee operates between 52 and 71 GHz, while the modified triangle bias tee functions within a frequency range of 50–79 GHz, achieving insertion losses of approximately 1.3–1.6 dB and a DC/RF isolation around 20 dB. These designs utilize a specialized PCB fabrication technique with a 0.1 mm design resolution [Umar *et al.*, 2021a]. Two additional bias tees, shown in Figure 1.2(e), are designed for X-band applications using modified structures: one with a single band-stop filter (BSF) unit and another with two BSF units. The conventional radial stub is modified by connecting two shunt open stubs to create a BSF with a wide rejection band, enhancing RF-to-DC isolation. However, the use of microstrip technology in this structure introduces significant loss and unwanted surface wave mode propagation at millimeter-wave frequencies [Jana *et al.*, 2019a]. Lastly, Figure 1.2(f) illustrates a planar broadband bias tee intended for integration within the intermediate-frequency (IF) circuitry of on-chip room-temperature broadband detectors. The design achieves an isolation (S_{31}) below -10 dB at 14.45 GHz, with S_{33} observed above -2 dB at 13.1 GHz. Despite these performance gains, the bandwidth of this bias tee remains limited due to the semi-open structure of the microstrip, which is susceptible to radiation loss at higher frequencies [Yadav *et al.*, 2022].

Overall, advancements in broadband millimeter-wave bias tee designs have yielded substantial performance enhancements, making them increasingly viable for a wide range of high-frequency applications. Nevertheless, challenges such as managing parasitic effects and ensuring manufacturing precision remain significant obstacles. To address these issues and further improve bias tee performance in millimeter-wave applications, ongoing innovation and research are essential.

1.2.2 Amplifier

An amplifier is a critical component in RF front-end systems, playing a key role in enhancing weak signals received by the antenna while minimizing noise, thereby improving the signal-to-noise ratio (SNR). Recent advancements in amplifier technology, particularly in printed circuit boards (PCBs) for microwave applications, have been focused on optimizing performance metrics such as gain, linearity, bandwidth, and power handling capabilities. These improvements are driven by the growing demands of modern communication systems and other high-frequency applications.

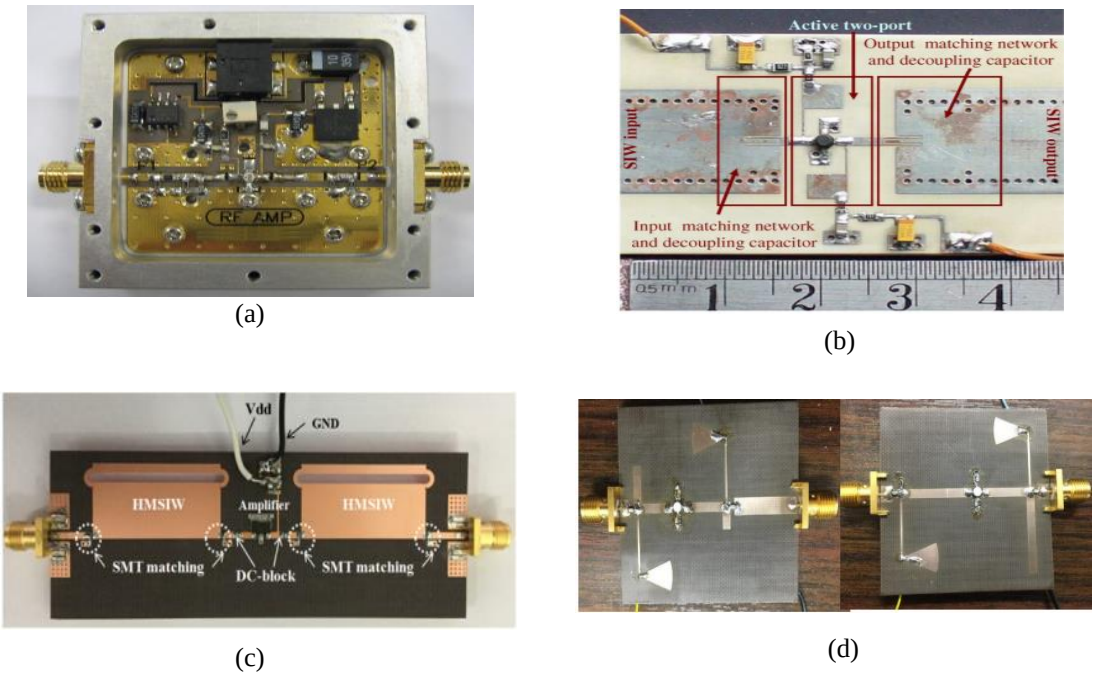


Figure 1.3 : (a) Single stage RF amplifier at 5.8GHz ISM band with IEEE 802.11a standard [Othman *et al.*, 2007];(b)X-Band Substrate Integrated Waveguide Amplifier [Abdolhamidi and Shahabadi, 2008]; (c) Half-mode substrate integrated waveguide amplifier using lumped-element transition[Eom and Lee, 2017]; (d) Optimization of LNA's first stage to reduce overall noise figure in multi-stage LNAs [Sabzi *et al.*, 2020a].

The development of advanced semiconductor materials, such as Gallium Nitride (GaN) and Gallium Arsenide (GaAs), has enabled amplifiers to achieve significantly higher gains. Additionally, the incorporation of broadband matching networks and sophisticated design methodologies has extended the effective operating frequency range of amplifiers. Innovations in thermal management have also contributed to enhanced power handling capabilities, meeting the requirements of increasingly compact and efficient designs. The trend toward miniaturization and the integration of analog and digital circuits on the same PCB has accelerated the development of more compact and sophisticated amplifiers. Material advancements, such as the adoption of PCB substrates with lower dielectric losses and improved thermal properties, have played a vital role in enhancing amplifier performance. Furthermore, the use of advanced design and simulation tools has enabled more precise and optimized amplifier designs, leading to the production of amplifiers that are more efficient, reliable, and capable of meeting the stringent requirements of contemporary high-frequency applications. In Figure 1.3(a), a single-stage RF amplifier designed for 5.8 GHz demonstrates reliable performance within its desired frequency range [Othman *et al.*, 2007]. However, transitioning to mmWave frequencies presents substantial challenges, including those related to stability, material selection, gain, impedance matching, and thermal management. Figure 1.3(b) illustrates a substrate-integrated waveguide (SIW)-based amplifier, which offers promising benefits for X-band applications, such as high gain with good impedance matching [Abdolhamidi and Shahabadi, 2008]. Figure 1.3(c) shows a half-mode substrate-integrated waveguide (HMSIW) amplifier featuring a lumped-element transition circuit that, while demonstrating potential in certain aspects, faces limitations in bandwidth, impedance matching, and integration, making it

less suitable for widespread mmWave applications [Eom and Lee, 2017]. In Figure 1.3(d), the design of the amplifier circuit highlights the critical trade-off between maximizing gain and achieving optimal input matching. Conventional design methods often prioritize minimizing the noise figure (NF) of the first stage, which can reduce overall gain and negatively impact the noise performance of subsequent stages [Sabzi *et al.*, 2020a].

Designing amplifiers presents several unique challenges when scaling up to mmWave frequencies. These include higher losses, tighter fabrication tolerances, material properties, and more trouble when combining different planar technologies due to the need for precise transitions and interconnects. Addressing these challenges requires advanced design techniques, a specialized fabrication process, and a high-quality measurement setup to fully leverage the potential of planar technology.

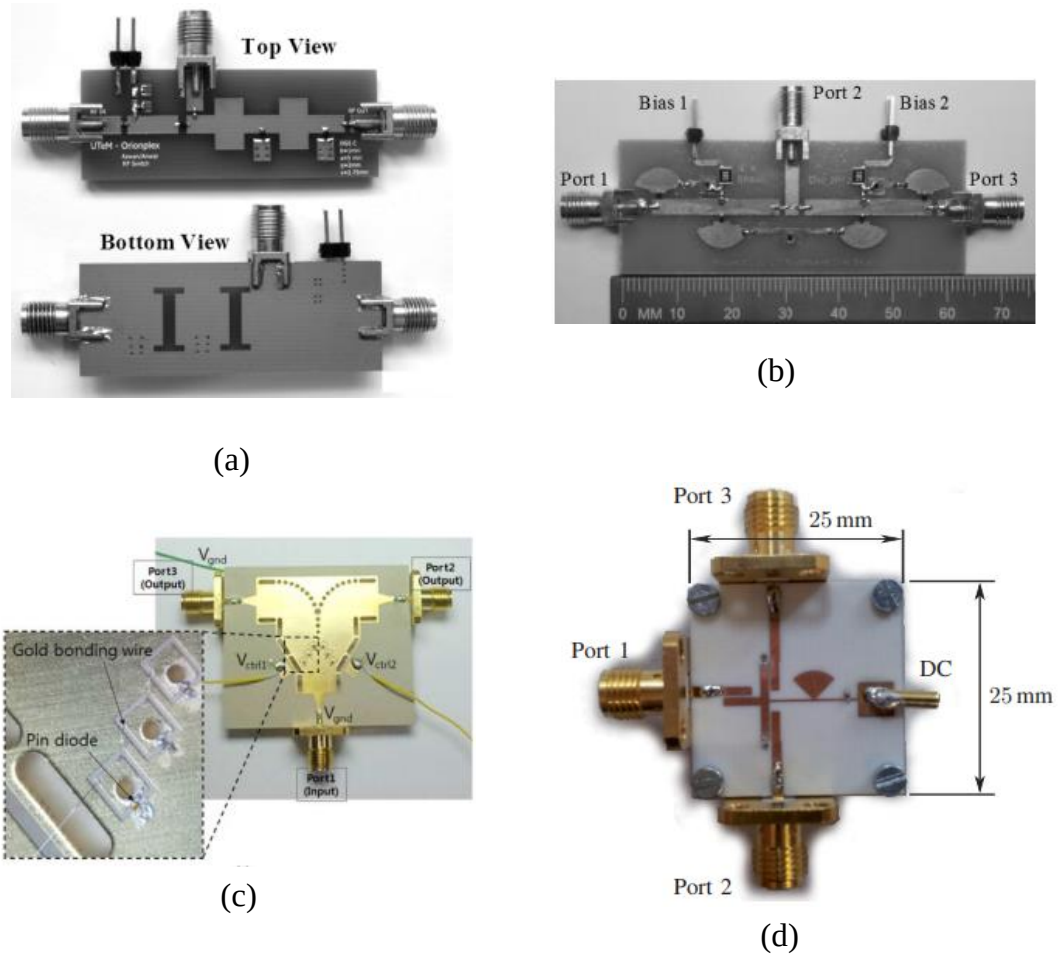


Figure 1.4 : (a)SPDT switch with defected ground structure for time division duplex switching in wireless data communication system [Shairi *et al.*, 2011a];(b)SPDT discrete switch design using switchable radial stub resonator for WiMAX and LTE in 3.5 GHz band [Shairi *et al.*, 2013]; (c) Substrate-Integrated-Waveguide (SIW) Single-Pole-Double-Throw (SPDT) Switch for X-Band Applications[Lim and Lim, 2014];(d) A compact bandpass filter integrated SPDT PIN switch at X-band [Rave *et al.*, 2014a].

1.2.3 SPDT switch

SPDT (single-pole double-throw) switches are essential components in RF front-end systems, facilitating the seamless routing of signals between transmit and receive paths. Their ability to provide high isolation, low insertion loss, rapid switching, and proper impedance matching makes them indispensable in a wide range of high-frequency applications.

Figure 1.4(a) illustrates an SPDT switch design incorporating a defected ground structure (DGS), which offers advantages such as reduced size and performance comparable to conventional switches [Shairi *et al.*, 2011a]. However, to achieve optimal performance in mmWave applications, this design must address critical challenges related to insertion loss, isolation, return loss, design complexity, and power handling. In Figure 1.4(b), the SPDT switch design uses single discrete PIN diode [Shairi *et al.*, 2013]. Although PIN diodes are commonly used in such applications, their performance degrades at mmWave frequencies, making it increasingly difficult to maintain high isolation alongside low insertion loss. Figure 1.4(c) demonstrates an SPDT switch design that achieves isolation above 15 dB within the frequency range of 6.52-10.12 GHz [Lim and Lim, 2014]. However, maintaining isolation performance becomes increasingly challenging due to tighter integration and greater coupling between components at higher frequencies. This circuit also incorporates a bias network for controlling the PIN diodes, where the complexity of the bias tee network can introduce additional parasitic elements that may adversely affect performance at mmWave frequencies. In Figure 1.4(d), an SPDT switch design is presented that introduces an insertion loss of approximately 2.4 dB [Rave *et al.*, 2014a]. Although this loss is within an acceptable range, it still represents a reduction in signal strength that must be minimized for optimal performance in mmWave applications. The integration of the switch into a bandpass filter results in a more compact design, but also introduces design complexities. Balancing the filter characteristics while ensuring efficient switching can be particularly difficult at mmWave frequencies.

1.2.4 Oscillators

Microwave oscillators are essential components in the generation of microwave signals, playing a critical role in a wide array of applications, including communication systems, radar, and electronic warfare. These oscillators are often implemented using printed circuit board (PCB) technology to achieve precise, stable, and tunable frequency generation. In Figure 1.5(a), Substrate Integrated Waveguide (SIW) resonator has emerged as promising elements in microwave circuits [Chen *et al.*, 2013], due to its cost-effectiveness and compatibility with PCB process. The implementation of this resonator at Ku band frequencies involves addressing several critical challenges such as managing radiation and parasitic losses, tuning the resonant frequency while maintaining a high Q factor, and ensuring consistent phase noise performance across the tuning range. Figure 1.5(b) shows the design of SIW-based oscillators which offer a viable solution for achieving low phase noise at Ku band frequencies [Yang *et al.*, 2015b]. However, these designs are inherently challenging due to their size, design complexity, sensitivity to manufacturing variations, and the need for performance optimization. Effective implementation of SIW technology in high-frequency applications demands precise engineering and high-quality fabrication to fully capitalize on its benefits. Furthermore, SIW oscillators, as described in [Thapa *et al.*, 2021a], provide several benefits, including a high Q-factor, compact size, and low phase noise, as depicted in Figure 1.5(c). However, they also face challenges, such as radiation losses, thermal management, and the precision required during fabrication. These factors must be meticulously managed to ensure optimal performance in Ku band applications. Lastly, the X-band oscillator design presented in Figure 1.5(d) employs an eighth-mode SIW bandpass filter [Thapa *et al.*, 2021b], which is a strong candidate for achieving compact size and low phase noise of the oscillators. However,

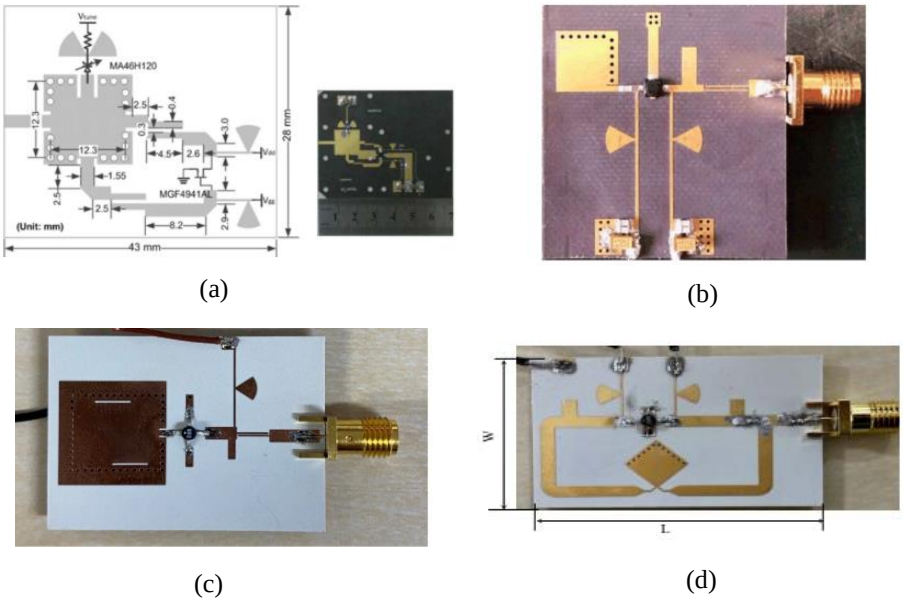


Figure 1.5 : Design of High-Q Tunable SIW Resonator and Its Application to Low Phase Noise VCO [Chen *et al.*, 2013];(b)Low phase noise oscillator based on quarter mode substrate integrated waveguide technique [Thapa *et al.*, 2021a]; (c) Miniaturized Slot-Loaded SIW Resonator and Its Application to C-band Low Phase Noise Oscillator [Thapa *et al.*, 2021a]; (d) X-Band Feedback Type Miniaturized Oscillator Design With Low Phase Noise Based on Eighth Mode SIW Bandpass Filter [Thapa *et al.*, 2021b]

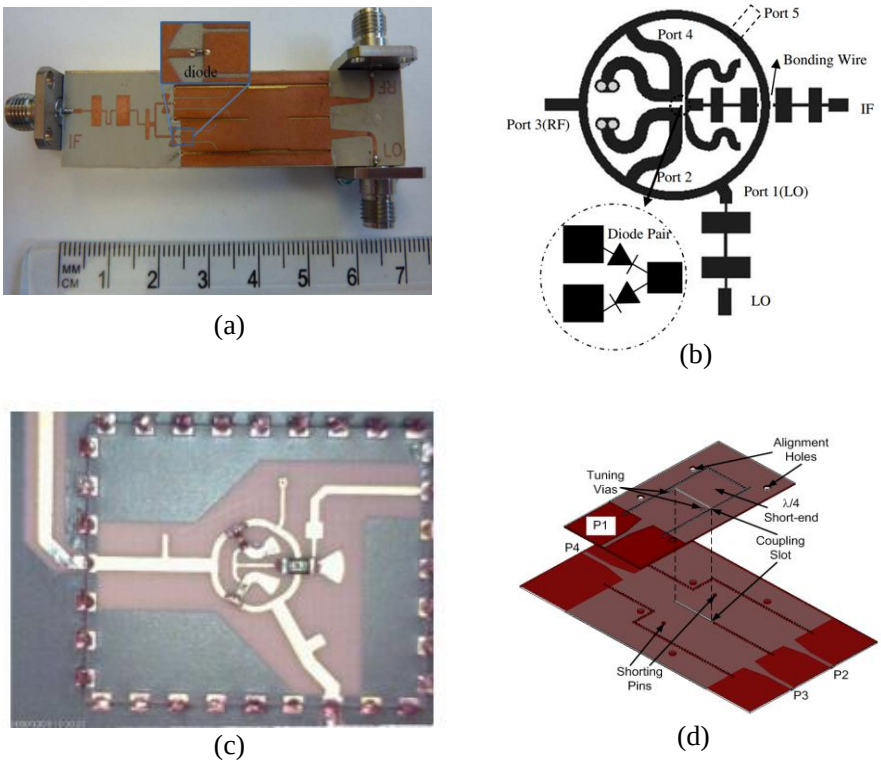
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the SIW structure at Ku band frequencies tends to be bulky, complicating the integration of other circuit components such as biasing networks, couplers, and filters when active elements are introduced. Engineers need to trade off between optimal performance and bulky transceiver system.

1.2.5 Mixer

A mixer is an essential component that facilitates frequency translation in the RF front end system. In the receivers section of RF front end, where signals need to shift to different frequency bands for modulation or demodulation, the mixer enables process enables the conversion of a signal from one frequency to another, making it indispensable. The mixer can be implemented using various components such as diodes, transistors, or other nonlinear devices. It operates by two input signals a local oscillator (LO) signal and Radio Frequency (RF) signal. The output signal is a combination of the sum and difference of these two frequencies, known as the intermediate frequency (IF). The performance of mixer is characterized by parameters such as conversion loss, isolation, and linearity.

Figure 1.6(a) shows the design of mixer using SIW technology [Zhang *et al.*, 2010], which exhibits better performance and integration capabilities. However, several challenges such as parasitic inductances and capacitances effect of the diodes need to be addressed to optimize its application in mmWave frequency. Overcoming these challenges requires advancements in fabrication techniques, improved design methodologies, careful consideration of integration and the



(a) (b) (c) (d)

Figure 1.6 : (a) 180-degree substrate integrated waveguide hybrid and its application to broadband millimeter-wave single balanced mixer design [Zhang *et al.*, 2010];(b) Design of a microstrip balanced mixer for satellite communication [Guo *et al.*, 2011]; (c) Development of low-cost 24-GHz circuits exploiting system-in-package (SiP) approach and commercial PCB technology [Alimenti *et al.*, 2012a] ; (d) Singly balanced mixer using substrate integrated waveguide magic-T structure [Han *et al.*, 2008].

use of advanced packaging technologies that minimize interconnect lengths and unwanted coupling. In Figure 1.6(b), the mixer exhibits challenges in effectively rejecting spurious signals, particularly the even harmonics of the local oscillator (LO) and radio frequency (RF) signals, along with their intermodulation products [Guo *et al.*, 2011]. This inadequate spurious rejection has the potential to degrade the overall performance of the mixer significantly. Furthermore, maintaining critical performance metrics, including amplitude and phase balance, becomes increasingly difficult at Ka band. Ensuring these parameters adhere to the stringent specifications required for optimal mixer functionality. Figure 1.6(c) shows the packaging of the mixer which is included the integration of diodes and associated components within the rat-race hybrid [Alimenti *et al.*, 2012a]. It needs to be precise to minimize parasitic and ensure reliable performance at Ka band. Figure 1.6(d) shows that the design of hybrids (180-degree) is critical because it significantly impacts return loss, isolation, and spurious response characteristics [Han *et al.*, 2008]. Ensuring optimal hybrid design for balanced mixers can be complex and challenging.

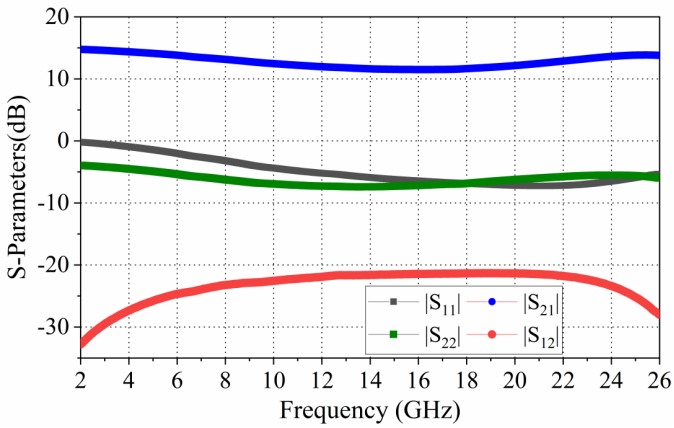
Designing high-performance mmWave active circuits demands SMD components that are optimized for low-loss, stable operation, with advanced packaging and assembly techniques that maintain performance at extremely high frequencies. These components are key to the development of reliable, high-frequency systems in modern communication, which are described below.

1.3 SMD COMPONENTS FOR MICROWAVE/MM WAVE ACTIVE CIRCUITS

Designing active circuits for microwave and millimeter-wave (mmWave) frequencies is a complex process that requires the careful selection of Surface-Mount Device (SMD) components. These components must be capable of handling high-frequency signals while maintaining a high Q-factor, low noise, low loss, and high linearity. Such characteristics are essential for applications

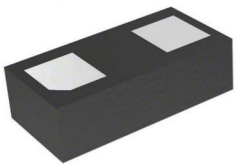


(a)

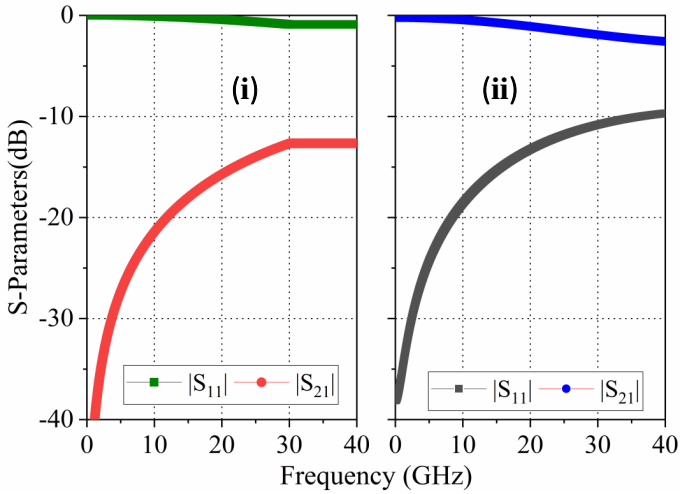


(b)

Figure 1.7 : (a) Physical model of pHEMT RF JFET transitor (CE3520K3);(b) Response of CE3520K3 model Laboratories [CEL].



(a)



(b)

Figure 1.8 : (a) Physical model of MA4E1317(Schottky diode); (b) Performance of MA4E1317 Model (i) at Reverse bias, (ii) Forward bias MACOM [2023].

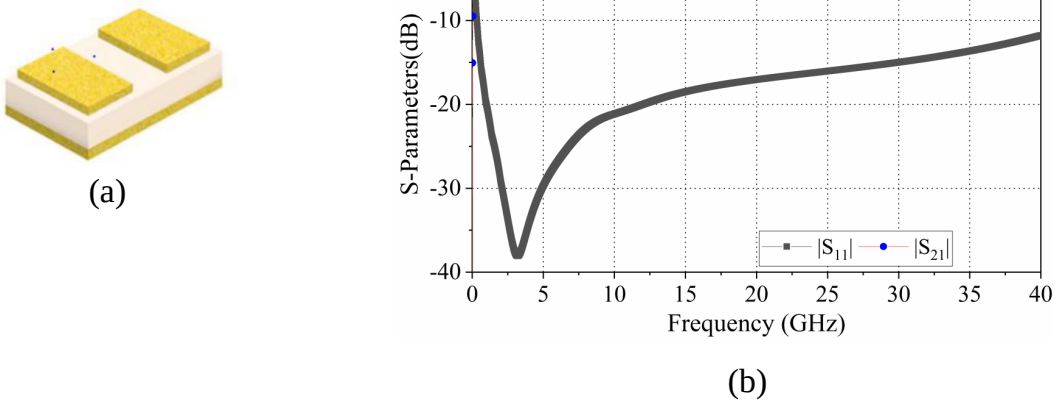


Figure 1.9 : (a) Physical model of gap capacitor (Tecdia AMG250K2BG);(b) Response of AMG250K2BG Tecdia [1985].

across telecommunications, radar, and signal processing. The selection of SMD components for key circuit elements like transistors, diodes, and capacitors at mmWave frequencies involves a meticulous evaluation of various parameters to ensure optimal performance.

In the amplifier and oscillator circuits, high-performance transistors are vital at mmWave frequencies. The chosen transistors must have a cutoff frequency (f_T) and maximum oscillation frequency (f_{max}) that are significantly higher than the operating frequency to ensure reliable performance. Additionally, a high gain is necessary to compensate for inherent losses in the system. In the thesis, the transistor model CE3520K3 is considered for mmWave frequency applications, as depicted in Figure 1.7(a). The S-parameters performance of the CE3520K3 transistor model, illustrated in Figure 1.7(b), demonstrates its suitability across the DC-26 GHz range, confirming its effectiveness in the designed circuits. Similarly, diodes are crucial for switching and mixing applications at mmWave frequencies. The diode's capacitance and series resistance must be low enough to ensure efficient operation, which requires careful evaluation of the diode's cutoff frequency. For switching and mixer applications, the diode's switching speed must be fast enough to handle the high frequencies involved. Furthermore, the diode must have a sufficiently high breakdown voltage to prevent failure under operating conditions, and it must exhibit low package parasitics to avoid performance degradation at high frequencies. In this thesis, the Schottky diode model MA4E1317 is selected for mmWave frequency applications, as shown in Figure 1.8(a). The S-parameters performance, shown in Figures 1.8(b)(i) and 1.8(b)(ii), illustrates the diode's suitability under both reverse and forward bias condition from DC to 40 GHz.

Lastly, capacitors are essential for DC blocking applications where their self-resonance frequency (SRF) must exceed the operating frequency to ensure that the capacitor remains primarily capacitive in nature. Low equivalent series resistance (ESR) is critical to minimize losses and maintain signal integrity. Additionally, minimizing the parasitic inductance and resistance of the capacitor is crucial, as these factors can significantly impact performance at mmWave frequencies. In this thesis, the capacitor model AMG250K2BG (25pF) is utilized for mmWave frequency applications, as shown in Figure 1.9(a). The S-parameters performance, depicted in Figure 1.9(b), confirms the capacitor's suitability for DC-40 GHz. This detailed component

selection process underscores the importance of choosing precise SMD components in the design of high-frequency circuits, ensuring that the circuits perform optimally across their desired frequency ranges.

1.4 DISCUSSION ON PLANAR TECHNOLOGIES

In modern RF front ends, planar technology plays a crucial role in advancement of modern RF front end to improve the performance and miniaturization of the system. There are several reasons for the wide use of planar transmission lines. First of all, they are broadband while providing compact dimensions and light weight. Foremost, they are generally economical to produce as they are readily adaptable to hybrid and monolithic integrated circuit fabrication technologies at RF and microwave frequencies. Each of these types offers certain advantages with respect to other types. In general, planar transmission lines consist of strip metallic conductors, usually produced by some photo-lithographic process, on a nonconducting substrate. Typical substrate materials are slabs of dielectric, ferrite, or high-resistivity semiconductors. In most cases, there are metal ground planes that can either be printed on the same substrate or be a part of the metal housing of a microwave integrated circuit (MIC). The following types of planar transmission lines are commonly used for microwave-integrated circuits (MICs):

1. **Stripline:** Stripline is a type of transmission line characterized by a strip conductor that is centrally positioned between two parallel ground planes. This strip conductor is separated from the ground planes by two equal slabs of a dielectric, ferrite, or semiconductor medium. The dielectric medium typically consists of a solid material, providing mechanical support and dielectric properties essential for signal propagation. However, in certain applications where lower losses or specific impedance characteristics are required, air can be utilized as the dielectric medium, effectively minimizing dielectric losses and enhancing the performance of the stripline. At millimeter-wave (mmWave) frequencies, the physical size of components and interconnects becomes very small, and the proximity of these components can lead to significant electromagnetic coupling and crosstalk. This makes stripline, which typically provides good shielding at lower frequencies, less effective at higher frequencies since it lacks the necessary lateral shielding to prevent these unwanted interactions.

2. **Microstrip Line:** The microstrip line is a transmission line geometry with a single conductor trace on one side of a dielectric substrate and a single ground plane on the other side. Since it is an open structure, microstrip line has a major fabrication advantage over the stripline. It has low profile and good integration ability, but is not preferable for operation in millimeter wave frequency range due to radiation loss. It also suffers from surface wave loss and high conductor loss at high frequency of operation. Gold plated microstrip lines are used to combat with the conductor loss but usage of such expensive material makes it commercially not feasible.

3. **Grounded Coplanar Waveguide (GCPW):** Grounded coplanar waveguide (GCPW) is advantageous over stripline and microstrip at millimeter-wave (mmWave) frequencies due to its ability to confine electromagnetic fields more effectively, which reduces radiation loss. It also offers better impedance control and easier integration with surface-mount components. However, GCPW can suffer from higher conductor loss due to the proximity of the signal to the ground planes and is more challenging to manufacture precisely. Additionally, it is more prone to parasitic modes and does not offer the same level of isolation as stripline.

4. **Substrate Integrated Waveguide (SIW):** Substrate-integrated waveguide (SIW) has significant advantages over grounded coplanar waveguide (GCPW), stripline, and microstrip

at millimeter-wave (mmWave) frequencies. SIW offers superior performance in terms of low insertion loss and high-quality factor due to its ability to confine electromagnetic energy within the substrate, reducing radiation losses that are prevalent in GCPW and microstrip designs. Substrate-integrated waveguide (SIW) occupies a larger footprint compared to TEM-based technologies and exhibits a narrower single-mode bandwidth. However, it remains a suitable technology for system implementation.

5. **Substrate Integrated Coaxial Line:** The Substrate Integrated Coaxial Line (SICL) technology presents an innovative solution for microwave and millimeter-wave active circuits by offering broad bandwidth through uni-modal TEM-based transmission in a compact form factor. SICL, essentially a printed version of traditional coaxial lines, is constructed by confining a metallic strip laterally with copper-deposited vias on both sides and metallic plates enclosing it. This configuration, illustrated in Figure 1.10, is self-shielded and self-packaged, making it an attractive option for RF front-end design.

   SICL technology reduces feed network losses and mutual coupling in antennas and antenna arrays. Moreover, designing bias lines and intermediate connections between transistors and matching networks in the shielded SICL environment, ensures low loss and excellent signal integrity. Passive components such as filters and couplers can be designed compactly with high Q and low-loss resonators, offering wideband mono-mode TEM characteristics. Figure 1.11 (a) and (b) show the top and cross-sectional view of SICL, respectively. The coaxial-like radially outward E-field vector of SICL transmission line, as shown in Figure 1.11(c), confirm that SICL is the planar form of traditional coaxial lines. The S-parameters demonstrate wide-band mono-mode propagation from DC to 50 GHz with minimal insertion loss, verified through high-frequency structural simulations (HFSS) in Figure 1.11 (d). The diameter (D) of via, spacing between vias (s), and distance between rows of vias (A) are critical in ensuring single-mode TEM propagation up to the occurrence of next higher order mode (TE_{10}) with Eq (1.1) as shown in Figure 1.11(e). The next higher order mode can be defined by Eq (1.1) [Ali *et al.*, 2023].

$$f_{TE_{10}} = \frac{c}{2\sqrt{\varepsilon_r}}\left(A - \frac{D^2}{0.95 \times s}\right) \tag{1.1}$$

Advantages of SICL Technology

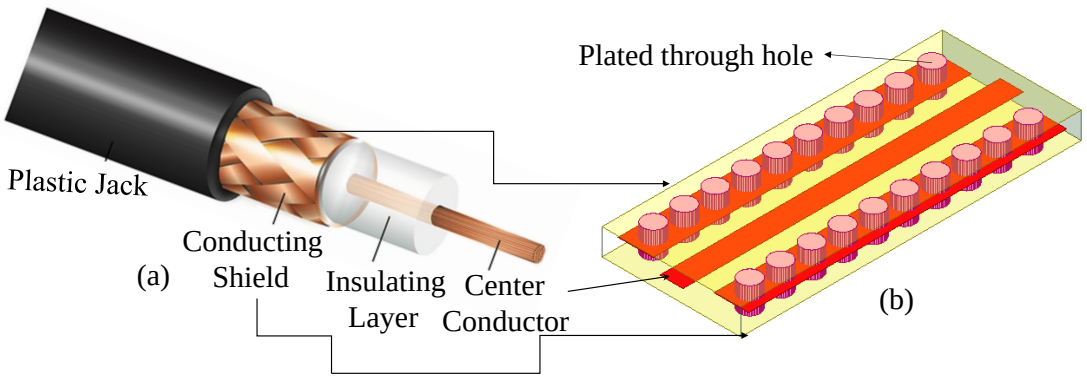


Figure 1.10 : Structural similarity between (a) a conventional coaxial line[Media, 2021] ;(b) a substrate integrated coaxial line (SICL)

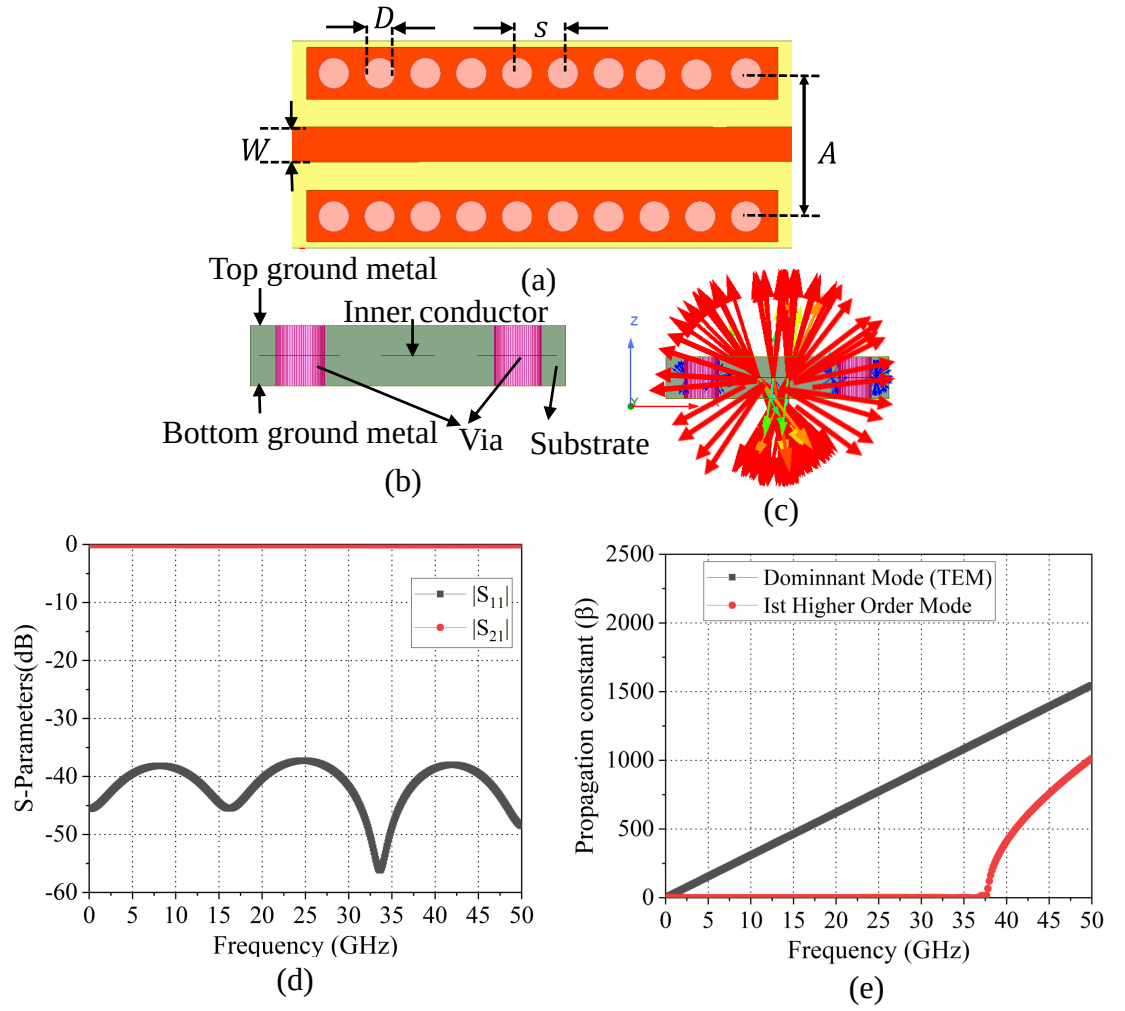


Figure 1.11 : (a) Physical layout of SICL line with dimension of $D = 0.4$ mm, $s = 0.6$ mm, $A = 3$ mm, $W = 0.45$ mm;(b) a cross section view of SICL; (c) Field distribution of SICL line;(d) Performance of SICL line; (e) Variation in modes frequency as function of β

- **Compact Form Factor:** Efficient use of space.
- **Self-Shielded and Packaged:** Reduces external interference.
- **Low Loss and High Signal Integrity:** Useful for the bias lines and intermediate connections.
- **Reduced Feed Network Losses and Mutual Coupling:** Beneficial for antennas and antenna arrays.
- **WideBand Mono-Mode (TEM mode) Propagation:** Confirmed from DC to 50 GHz.

By leveraging these benefits, SICL technology is poised to significantly enhance the performance and integration of microwave and millimeter-wave systems. Recent research

has explored various SICL-based components and systems, including: Transitions [Wei *et al.*, 2015], Filters [Cariou *et al.*, 2016], Antennas [Liu *et al.*, 2019] ,Baluns [Zhu *et al.*, 2012],Oscillators [Chen *et al.*, 2014] Additionally, an SICL-based high-speed data transmission system [Shao *et al.*, 2017b] has been developed and tested, demonstrating a data rate of 30 Gb/s per channel. SICL provides excellent electromagnetic compatibility for densely packaged systems, and the non-dispersive nature of SICL makes it a worthy candidate for the implementation of circuits at millimeter-wave frequency. In recent time, SICL based transitions [Wei *et al.*, 2015], filters [Cariou *et al.*, 2016], antennas [Liu *et al.*, 2019], baluns [Zhu *et al.*, 2012], and oscillators [Chen *et al.*, 2014] have been investigated.

Type of Transition with SICL Transmission Line

Several novel technologies have emerged recently for designing millimeter wave circuits in a planar form. With the increasing complexity of system designs and the use of different fabrication technologies, low-loss broadband interconnects are essential for effective system performance. This integration enhances system functionality and performance. The Substrate Integrated Coaxial Line (SICL), also known as fenced stripline[Wu *et al.*, 2014b] is notable for its low loss at millimeter-wave frequencies and its ability to prevent undesired parallel plate modes. It offers excellent electromagnetic compatibility for densely packaged systems and is non-dispersive, making it ideal for millimeter-wave circuits. Transitions between various technologies, such as microstrip line, substrate integrated waveguides (SIW), and grounded coplanar waveguides (GCPW), to SICL technology [Krishna and Mukherjee, 2019] ,[Tao *et al.*, 2019],[Liu *et al.*, 2013] have been successfully demonstrated as shown in Figure 1.12(a),(b)

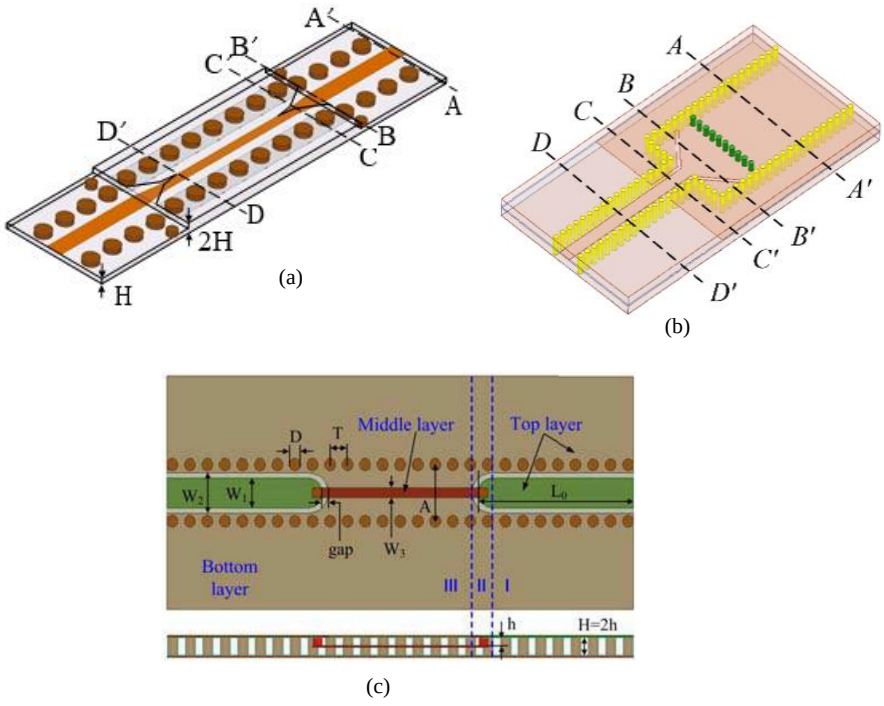


Figure 1.12 : Various transition to SICL technology (a) Microstrip to SICL transition Krishna and Mukherjee [2019];(b) SIW to SICL transition Tao *et al.* [2019]; (c) GCPW to SICL transition Liu *et al.* [2013]

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and (c). These transitions are crucial for integrating SICL into different systems. Various techniques, such as using metallic via holes and coupling apertures, have been developed to facilitate these transitions. Several studies have validated the effectiveness of these transitions, with results showing low insertion losses and good return loss performance across various frequency bands. In this thesis, SICL-to GCPW transition is preferred as shown in Figure 1.13(a). The S-parameters performance of the transition is shown in Figure 1.13 (b), whereas it can significantly impact performance beyond 38 GHz due to the occurrence of unwanted modes, particularly when discontinuities are present in the transition.

To overcome the limitations and challenges faced by previous active circuit designs, SICL-based active circuits offer a solution by enhancing integration, minimizing losses, and providing superior performance, especially at higher frequencies. These advancements make them highly suitable for cutting-edge research in microwave and millimeter-wave technologies.

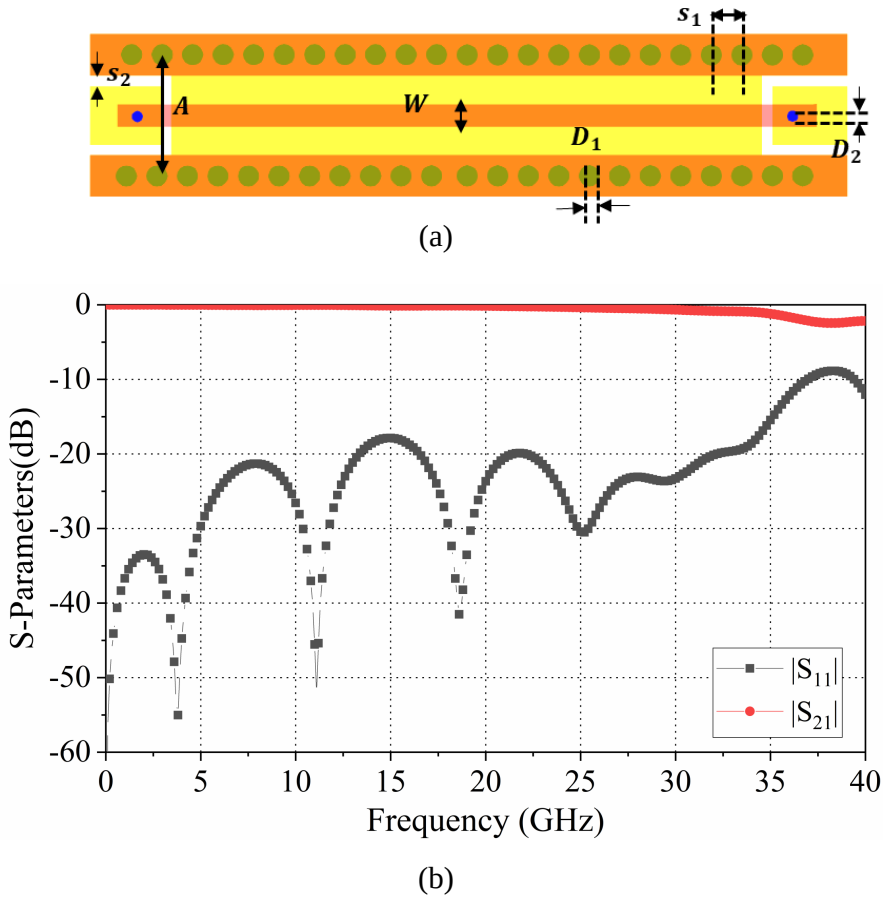


Figure 1.13 : GCPW to SICL transition; (a) Physical layout of the transition with the dimension of $D_1 = 0.4$ mm, $D_2 = 0.2$ mm, $s_1 = 0.6$ mm, $A = 2.88$ mm, $W = 0.45$ mm,$s_2 = 0.2$mm; (b) S-parameters response of the transition.

1.5 ORGANIZATION OF THESIS

In the thesis, there are seven chapters, the first of which is an introduction to a new technology known as substrate-integrated coaxial lines and the necessity of this technology in wireless systems of the current generation. This transmission line's application and working mechanism are examined in detail. The bias tee network, amplifier, SPDT switch, oscillator, and mixer are just some of the components that play a significant role in the modern RF front end. These components are studied in detail. Additionally, the latest and most advanced literature is examined in the specific area of microwave and millimeter-wave circuits to improve their functionality.

Chapter 2 starts the study of bias tee network using Substrate Integrated Coaxial Line (SICL) technology operating in K and Ka-band (20-29 GHz). The novelty of this work lies in realization of interconnecting pads to mount SMD capacitor in SICL environment. The bias tee design is validated with equivalent circuit model of mounting pads which can be used for designing SICL based active circuits using SMD components. This design uses a conventional low-cost PCB design technique while maintaining good insertion loss and isolation between RF and DC port and presents a low profile, simple design technique to realize mm wave active circuits in planar substrate.

Chapter 3 is dedicated to the design of a Ka-Band Single-Pole Double-Throw (SPDT) switch for duplexer applications using Substrate Integrated Coaxial Line (SICL) technology at 27-28.5 GHz. By leveraging a conventional low-cost PCB design technique, the proposed switch achieves efficient performance suitable for Ka-band frequencies. An innovative RF isolation network is incorporated within an asymmetric stripline environment to facilitate the biasing of the switches, ensuring optimal isolation and performance. The functionality and performance of the SPDT switch circuit are thoroughly analyzed through an equivalent circuit model of the RF isolation network. The results demonstrate that the proposed SPDT switch circuit is highly effective for Ka-band duplexer applications, offering a cost-efficient and reliable solution for modern communication systems.

Chapter 4 explores design and implementation of a single-stage amplifier operating at 24 GHz using Substrate Integrated Coaxial Line (SICL) technology, making a novel approach in the realm of low-cost printed circuit board (PCB) design techniques for millimeter-wave ISM band amplifier circuits. The design incorporates mounting pads on the top conductor within the SICL environment to facilitate the integration of transistors and capacitors (DC Block). Additionally, a novel matching network is introduced to enhance the amplifier's gain. The matching networks are thoroughly analyzed with a set of design graphs to aid in achieving the desired matching response. This work demonstrates the viability and effectiveness of SICL technology in high-frequency amplifier applications, offering a promising avenue for future research and development.

Chapter 5 deals with an innovative and cost-efficient approach to design a high-performance reflection oscillator using SICL technology at 15 GHz, targeting applications in the Ku-band frequency spectrum. This technique involves the use of a SICL based resonator to create a reflection oscillator circuit. The SICL resonator helps to achieve low-phase noise and delivers a significant output power of 12 dBm. The oscillator circuit demonstrates high suitability for Ku-band circuit applications.

Chapter 6 focuses on the design and implementation of downconverter mixer at 24-32 GHz. The size of the proposed mixer is $3.6\lambda_g \times 3.4\lambda_g$ where λ_g is the guided wavelength at centre frequency. The single-balanced mixer is realized by using a configuration of a SICL based rat-race hybrid ring with five ports and two MA4E1317 GaAs Schottky diodes. The IF extraction circuit is introduced at the fifth port of the rat race hybrid ring with pass band from DC to 8 GHz. The

measured conversion loss is less than 13 dB from 24 to 32 GHz. The measured port isolations of LO-RF, RF-IF, and LO-IF ports are greater than 24 dB.

The thesis is finally concluded in **Chapter 7**, which also addresses the future scope of SICL-based active circuits.