1 Introduction

Modern electronic communication technology has been broadly classified into: (a) *wired* (landline telephony, fiber-optic networks, power line transmission, etc.) and (b) *wireless* (bluetooth, mobile systems, Wi-Fi, etc.). The idea of wireless communication originated from James Clark Maxwell's mathematical formulations on electromagnetic (EM) waves in 1867. However, the first wireless communication in the history was done by an italian inventor, Guglielmo Marconi. He transmitted Morse code signals using radio waves wirelessly to a distance of 3.2 KMs in 1895 using the mercury Coherer realized by Sir J. C. Bose [Bondyopadhyay, 1998]. It was in 1973 that first cell phone call was made possible by American engineer, the "Father of Cell Phones" Martin Cooper at Motorola. Since then the modern communication system has witnessed remarkable advancements, transforming the way we connect, communicate, and access information. The mobile communication has evolved from first generation (1G) to fifth generation (5G) in past few decades.

The first real milestone in mobile phone communication that we use today happened in 1980s. The birth of the mobile phone communication: 1G, used analogue technology as AMPS (Advanced Mobile Phone System) in the United States and the NMT (Nordic Mobile Telephone) System in Europe for voice transmission at 800 MHz using FM modulation. It was highly insecure form of communication as it lacked encryption and the no-roaming feature made it even more unattractive. Later, with the advent of digital communication in 1990s also known as Global System for Mobile Communication (GSM), 2G marked a significant leap that revolutionized the mobile telecommunication industry. Improvement in quality of voice, making communication secure by encrypted voice transmission made 2G popular. Code Division Multiple Access (CDMA) systems developed by Qualcomm were also introduced that adds more features than GSM regarding spectral efficiency, number of users, and data rate. The highlight in 2G was the introduction of Short Message Service (SMS) and low speed internet. With the introduction of UMTS (Universal Mobile Terrestrial/ Telecommunication Systems), 3G was introduced in the new millennium in the early 2000s ushering the era of the modern communication. The third generation of mobile communication facilitated faster data speeds, enabling users to browse the web, send emails, and access basic multimedia content on their phones. The early video calling in 3G utilized circuit switching and was billed per minute making it an expensive option. Around 2010, 4G networks emerged as the rise of mobile broadband, and they marked a substantial leap forward in mobile communication. 4G significantly increased the data speed, making high-speed internet browsing, real-time video streaming, online gaming and high-quality video calls a reality. The low-latency and high bandwidth allowed real-time data exchange between connected device, creating room for smart homes, wearable devices, and IoT innovations.

1.1 Motivation for 5G

5G is an emerging technology that is particularly engineered to provide connectivity across everyone and everything, including various objects, gadgets and machines. A pertinent query arises as to whether there is a genuine need for significantly faster connectivity, such as 5G, given the

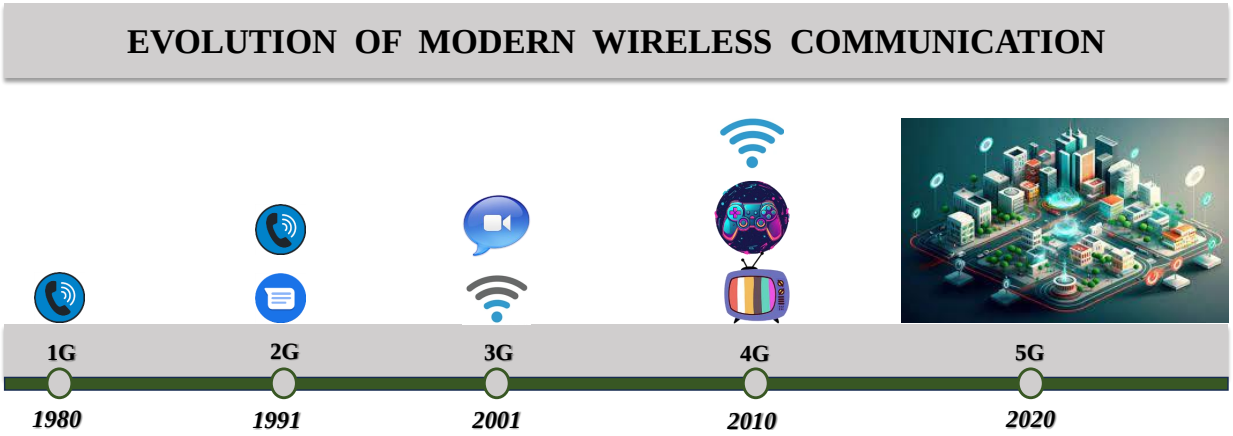


Figure 1.1: Roadmap illustrating the sequential development of contemporary wireless communication systems. (Courtesy: google images)

globe is currently clearly thriving with 4G services. This leads us to the motivation behind the study and development of fifth-generation (5G) wireless communication technologies.

The RF requirements for by 5G system targets for specifically higher data rates, reliable connectivity, and faster response times. Futuristic goal of virtual reality is useful in comprehending things beyond our reach. A possible use case can be a professor performing incisions and demonstrating various anatomical structures using a virtual cadaver. Augmented reality goggles, or holographic projector would be used to bring live movements in executing various such use-cases. This presents a multitude of concurrent three-dimensional (3D) high-definition (HD) links, all occurring within the exact same geographical area. This certainly exceeds the capability of both WiFi and 4G network.

This leads us to the Next Generation (xG) paradigm, which employs a large number of antennas in access points to provide a high level of spatial multiplexing for various devices, ranging from mobile phones and tablets to Internet of Things (IoT) devices. These access points utilize a hierarchical wireless mesh network to provide self-backhaul, eliminating the necessity of using cables or fiber for the backhaul network. The access point has the ability to activate, recognize other nodes within the network, and start the process of directing traffic as needed. This is done in a dynamic manner, similar to the way the Internet and packet switching operate, where connections may be established or terminated as required. Simultaneously, the scope of 5G and its potential to employ higher-frequency bands in order to achieve greater spectral efficiency and overcome interference was envisioned. Consequently, the concept of 5G operating in the millimeter-wave range emerged [Samsung, 2018].

1.2 5G: Unveiling the Future

The Next Generation (xG) vision as mentioned above is more or less what is being discussed today as 5G. 5G is not limited to specific new radio-access technology, but rather covers a wide range of new services envisioned for future mobile communication.

Radio communications sector of the International Telecommunications (ITU-R) has defined three distinctive potential use cases for 5G networks [ITU-R, 2015]: enhance mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (URLLC) as shown in Fig. 1.2. eMBB represents the natural progression of mobile

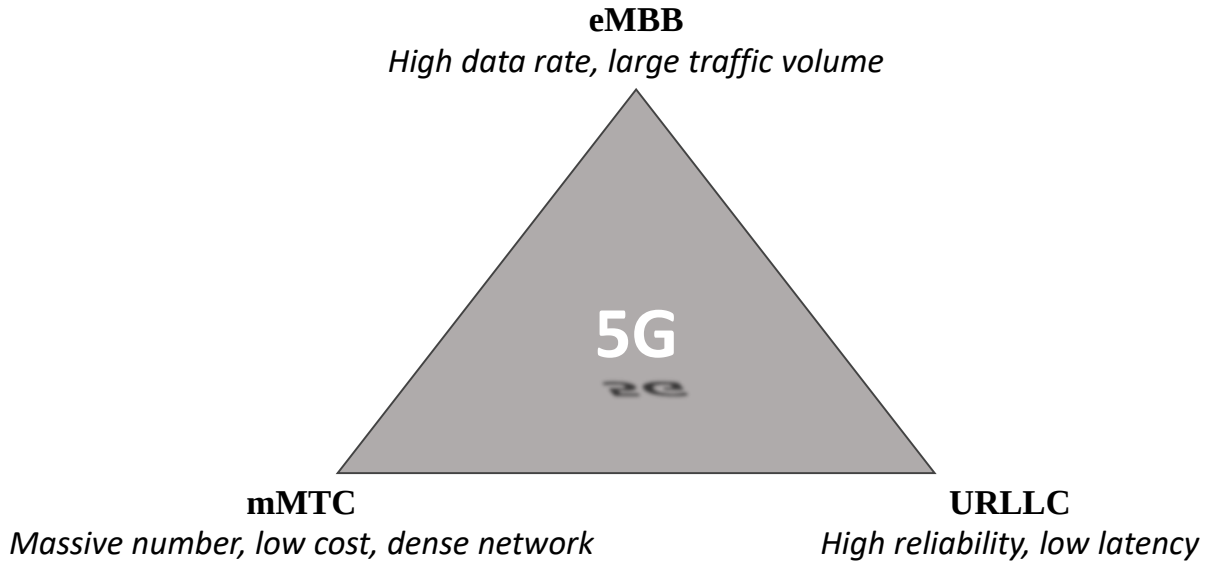


Figure 1.2: 5G use-cases.

broadband data services, which continues to be the core application of mobile communication systems. It is distinguished by its high data rates and substantial traffic volumes. 5G will enhance the user experience by providing high-speed mobile connection for eMBB applications. mMTC corresponds to services like Internet of Things (IoT) that are characterized by a massive number of devices. Key requirements of such services include low device complexity, low energy consumption, long battery life time, and significant coverage extension, in addition to the supporting massive number of devices. URLLC refers to mission critical services that need extremely high dependability and minimal latency. The classification of 5G use cases into these three distinctive classes is a starting point, that aims to simplify the definition of requirements of the technology specifications.

The Radiocommunication sector of International Telecommunications (ITU-R) started a program in early 2012, to develop International Mobile Telecommunications (IMT) for 2020. IMT-2020 defines technical requirements, as summarized in Table 1.1. The goal is to make forthcoming cellular radio system ten or even a hundred times better than the current state-of-the-art system based on Long Term Evolution Advanced (LTE-A). As mentioned in Table 1.1, 5G will deliver data at much higher data rates that aims at enhancing the mobile broadband experience. The overall efficiency of 5G is targeted to be improved by three times compared to 4G. It is anticipated to have a 10 x densification of base station aiming to meet the requirements of mMTC scenarios. Improved latency and energy consumption are also a key considerations.

1.3 5G Spectrum

Historically, the first and second generation of mobiles services were assigned at frequencies around 800-900 MHz and in some lower and higher bands. With the introduction of third generation (3G) in IMT-2000 focus shifted onto 2 GHz band. Its continuous expansion of IMT services with 3G and 4G new bands were added at both lower and higher bands.

Due to the propagation properties, bands at lower frequencies are useful for wide area coverage deployments, in urban, suburban and rural environments. Higher bands to a large extent have been used to boost the channel capacity in dense deployments, as its propagation properties make it difficult for wide area coverage. 5G systems that are addressing ITU targets will be deployed

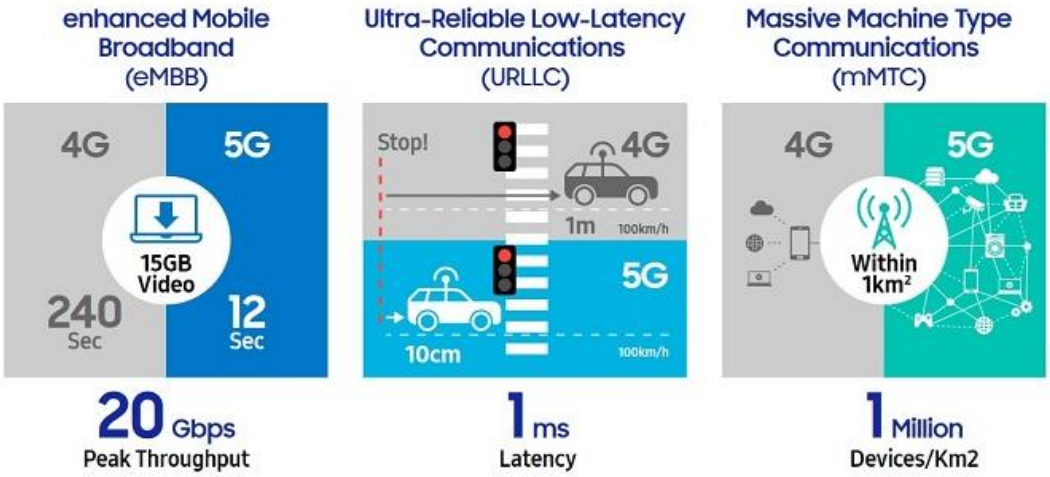


Figure 1.3: User services by 3GPP Release 15 to meet the requirements of ITUs IMT-2020s. (Courtesy: Whitepaper, Samsung, *3GPP Release 16 Shifting Gears to Increase 5G Speeds on Multiple Network Highways*, Oct, 2020.)

Table 1.1: Specifications of technical requirements by IMT-2020

Metric	**5G Target**	**Usage scenario**	**Impact to RF design**
Peak data rate	DL: 20 Gbps; UL: 10 Gbps	eMBB	Bandwidth, carrier frequency, EVM
User experienced date rate	DL: 100 Mbps; UL: 50 Mbps	eMBB; dense urban	Range, noise, spectrum sharing, EVM
Peak spectral efficiency	DL: 30 bps/Hz; UL: 15 bps/Hz	eMBB	EVM, linearity, noise, spatial/ spectral filtering
User spectral efficiency	DL: 0.3 bps/Hz; UL: 0.21 bps/Hz	eMBB; indoor hotspot	
	DL: 0.225 bps/Hz; UL: 0.15 bps/Hz	eMBB; dense urban	
	DL: 0.12 bps/Hz; UL: 0.045 bps/Hz	eMBB; rural	
Area traffic capacity	DL: 10 Mbps/m2	eMBB; indoor hotspot	Interference
User plane latency	4 ms	eMBB	Digital signal processing protocols
	1 ms	URLLC	
Connection density	10^6 devices per km^2	mMTC	Interference
Network energy efficiency	100 x	mMTC	From system to RF circuit details

(Source: [Dahlman *et al.*, 2018], and [Hueber and Niknejad, 2019].)

both at conventional frequency bands below 6 GHz, sub mm-wave (<30 GHz) and mm-wave (30-100 GHz) bands. New bands are being continuously defined by ITU and 3GPP, both for New Radio (NR) and LTE specifications. Paired bands are used for Frequency Division Duplex (FDD) operation, while unpaired bands are used for Time Division Duplex (TDD) operation. Broadly

these bands can be defined based on the spectrum usage as (a) Low-band spectrum, (b) Mid-band spectrum and (c) High-band spectrum [Lin and Lee, 2021]. Low-band spectrum exists below 1 GHz. Due to its desirable propagation properties, this spectrum is good for providing wide-area and deep indoor coverage. The channel bandwidth is narrow (e.g. 20 MHz). Mid-band spectrum spans over a frequency range of 1-7 GHz. It has better wide-area and indoor coverage properties. It can enable networks of large capacity, high data rates and low latency. The channel bandwidths of 50-100 MHz are possible in mid-band spectrum. High-band spectrum is defined for millimeter wave frequencies above 24 GHz, also known as FR2 mm-wave band. The wide-spectrum provides bandwidths for very high data rates and ultra large capacity. These bands are ideal for localized dense deployments to enable high-throughput and low-latency services. It is however difficult to provide wide-area coverage. Channel bandwidths of 400 MHz were initially proposed and the same have later been increased upto 3 GHz (NR n257 band).

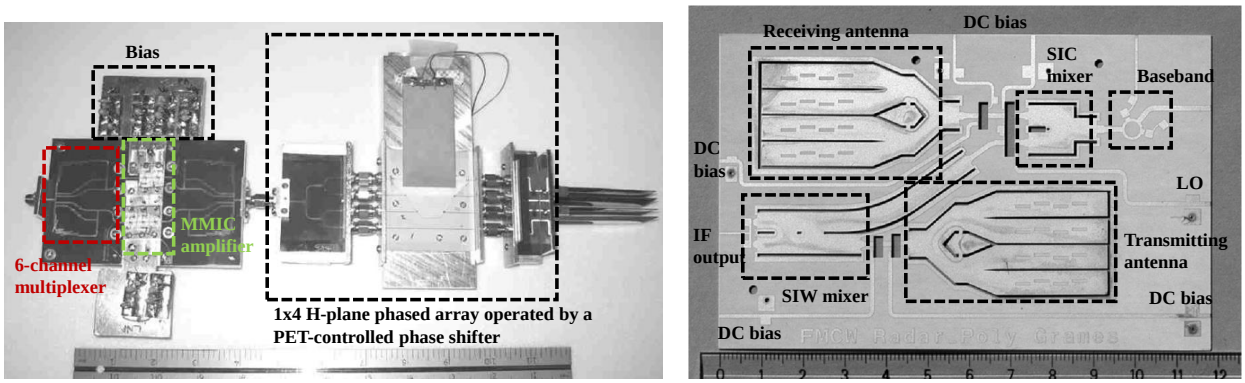
The World Radio-communication Conference (WRC) establishes and designates the frequency spectrum through the adoption of agendas. The World Radiocommunication Conference 2015 (WRC-15) was a significant event that paved the way for the development of 5G technology. The frequency range of 3300 - 4990 MHz, which is globally recognized and utilized in many nations, represents a novel spectrum allocation for 5G technology. Furthermore, a specific topic, labelled as agenda item 1.13, was designated for the World Radiocommunication Conference 2019 (WRC-19). The purpose of this agenda item is to determine the high-frequency bands above 24 GHz that can be used for International Mobile Telecommunications (IMT), based on the decisions made at the World Radiocommunication Conference 2015 (WRC-15). The ITU-R identified a new set of bands for International Mobile Telecommunications (IMT) during the World Radiocommunication Conference in 2019 (WRC-19). These bands primarily aim to support IMT-2020 and 5G mobile services. They comprise a combined frequency of 13.5 GHz, distributed throughout the following band ranges:

- 24.25 – 27.5 GHz (USA, UK, EU, China, Japan, India, Australia, Korea)
- 37 – 43.5 GHz (USA, Canada, Japan, Korea, India, Australia)
- 45.5 – 47 GHz
- 47.2 – 48.2 GHz
- 66 – 71 GHz (USA, Canada)

Among the high-frequency bands above 24 GHz, the highest interest is in the range 24.25 29.5 GHz, with assignment of 3GPP NR bands n257 and n258 bands. Channel bandwidths up to 3 GHz are defined for these bands, with even higher bandwidths possible through carrier aggregation. For operation in the new mm-wave bands above 24 GHz such as the n257, n258, n261 bands are being planned in China and India. In 2022, India has auctioned 26 GHz band for commercial usage to various telecomm operators.

1.4 Planar Technologies for 5G millimeter wave

There exists several technologies for efficient design of microwave and millimeter wave antenna system. Waveguides are quiet popular for operation at high frequencies, as they exhibit low loss and excellent stability to withstand environmental variations. Such systems are heavy and are non-planar in nature. Waveguide based designs become unsuitable for implementation in handheld devices because of its bulky nature. For planar applications, microstrip technology has been quiet popular. A full-beam scanning antenna transceiver system [Hong *et al.*, 2006] based on microstrip technology from 10 - 35 GHz enjoys compact and planar form-factor which is not achievable with waveguides. It is a semi-open structure that causes severe parasitic coupling and has high conduction loss at millimeter wave frequencies due to concentration of current density along the edges of microstrip line. In addition it suffers from conduction and surface-wave losses. Special attention is



(a) (b)

Figure 1.4: Review of various technologies to implement integrated system. (a) Microstrip technology based transceiver system wih beam scannning capability [Hong *et al.*, 2006]. (b) SIW based FMCW Radar Front-End System [Li and Wu, 2007].

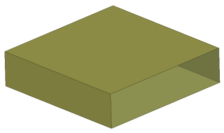
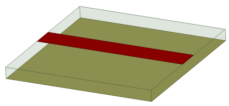
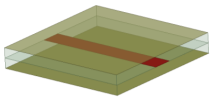
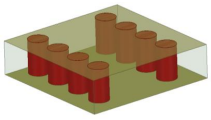
TECHNOLOGY	DESIGN	MERITS	DE-MERITS
1. Waveguide		• High power handling • Low loss • Excellent mechanical stability • No dielectric loss (air-filled waveguide)	• Bulky & non-planar • Narrowband mono-mode operation • Conductor & surface waves losses
2. Microstrip		• Low-profile & planar • Good integration ability	• Unshielded • Radiation loss at high frequency • Dielectric, conductor & surface waves losses
3. Stripline		• Low-profile & planar • Less lossy compared to microstrip	• Laterally unshielded • Radiation loss at high frequency • Dielectric, conductor & surface waves losses
4. SIW (Substrate Integrated Waveguide)		• Low profile & planar • Reduction in surface wave losses (lateral shielding)	• Narrowband mono-mode operation • Larger footprint compared to TEM guiding structure based designs • Dispersive wave propagation

Figure 1.5: A brief summary of different technologies involved in RF and microwave designs.

required for packaging of microstrip based circuits at high frequency and often a metal box is used to create a shielding environment. But such packaging finally increases the overall weight of the device. Gold plated microstrip lines are used to reduce the losses, but gold plated microstrip based designs are not a promising solution for mass-production and commercialization.

Substrate Integrated Waveguide (SIW), which is the planar implementation of waveguides, has emerged as one of the sought-after self-shielding planar guiding media. It incorporates waveguides in substrate by implementing two rows of vias (via-wall) to implement the sidewall of the waveguide in planar structures. Since SIW is a single-conductor technology, hence to implement active circuit in the system, microstrip lines are used [Li and Wu, 2007], that ultimately makes it lossy due to the high conductor and surface wave and radiation losses. SIW based systems occupy larger footprint than TEM guiding structure based circuits and can not offer broad single mode bandwidth due to its inherent narrowband mono-mode operation. A short-summary of these technologies is presented in Fig. 1.5.

1.5 Substrate Integrated Coaxial Line (SICL)

Researchers around the world have been looking for a novel technology that could address the issues discussed earlier for operation at 5G millimeter wave frequencies. [Gatti *et al.*, 2006] introduced a new technology, Substrate Integrated Coaxial Line (SICL), that provides a promising solution at mm-wave frequencies. The Substrate Integrated Coaxial Line (SICL) is considered the planar implementation of conventional rectangular coaxial line and hence it inherits many features of non-planar coaxial line. A middle metallic strip is sandwiched between top and bottom conducting plate supported by two substrates. Two parallel rows of metallic side via-walls along the middle strip provides lateral shielding to the transmission line. SICL provides several advantages over the well-known conventional transmission line technologies. SICL covers the short-comings in all the above mentioned conventional transmission lines as shown in Fig. 1.5. It provides dominant TEM mode unimodal wideband operation. It is shielded and non-dispersive in nature that preserves the propagating signal and can be readily fabricated using standard low-cost PCB fabrication technology. With the advent of SICL in designing antenna and antenna arrays, the losses in the feed network and the mutual coupling between the antenna elements could be minimized. SICL offers low-loss and excellent signal integrity for implementing bias lines and intermediate connections between transistors and matching networks in a completely shielded environment. Fig. 1.6 shows the different view of the designed SICL in a substrate of Taconic TLY-5A (ε_r=2.2). The structure of SICL is delimited by two rows on vias separated by distance A. The diameter of the via is D and spacing is S as shown in Fig. 1.6(c). Proper choice of the design parameter A, D and S ensures single-mode TEM propagation through the entire range of frequencies of interest which is

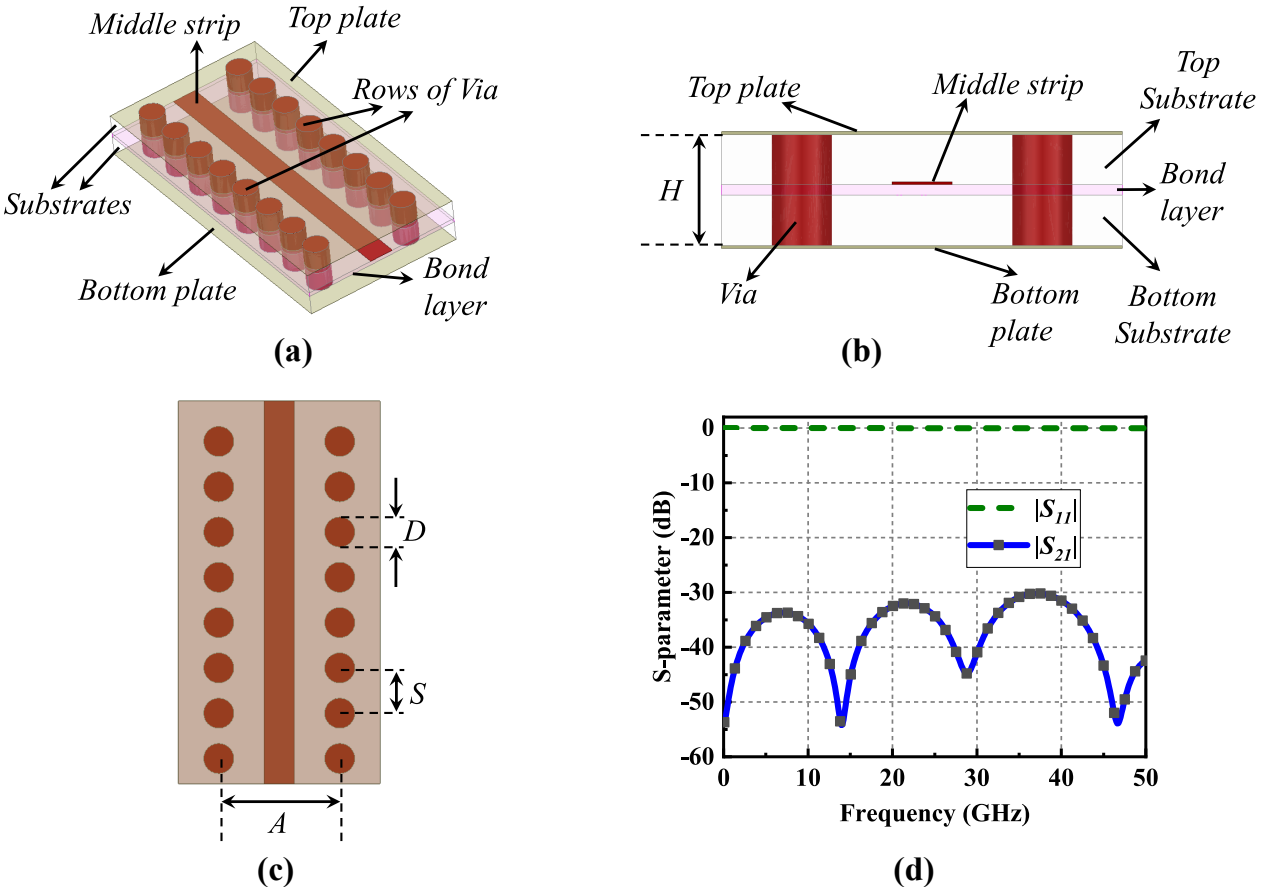


Figure 1.6: Design of Substrate Integrated Coaxial Line (SICL) in (a) isometric view, (b) cross-sectional view and (c) top view. (d) S-parameter performance of the designed SICL transmission line. Dimensions (in mm): H = 1.1, A = 2.4, S = 0.9, D = 0.6

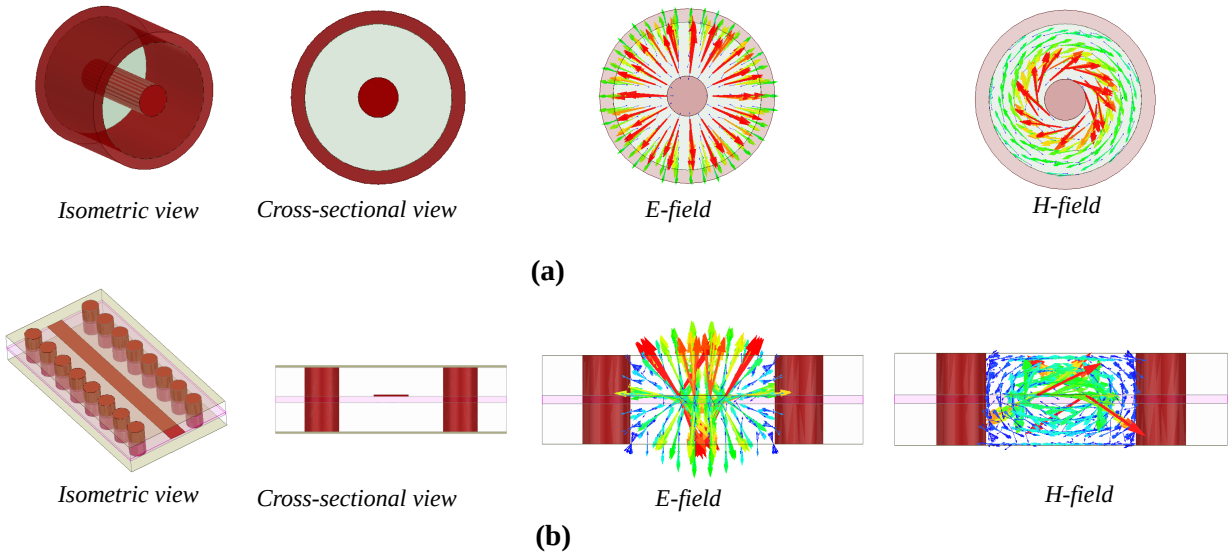


Figure 1.7: Design of (a) coaxial line and (b) Substrate Integrated Coaxial Line (SICL) with its filed distributions.

extended till the next TE mode (TE_{10}) is excited. The S-parameter is shown in Fig. 1.6(d) that depicts the performance of the designed SICL transmission line from DC to 50 GHz with very low insertion loss (< 0.1 dB) using Ansys High Frequency Structural Simulator (HFSS). By observing the radially outward directed E-field and concentric H-field in Fig. 1.7, it is confirmed that SICL is indeed planar implementation of the traditional coaxial line. The advantages of SICL technology are as follows:

1. Wideband unimodal operation
2. Shielded and non-dispersive wave propagation
3. Planar structure
4. Low losses
5. Low-cost & easy fabrication

SICL provides excellent electromagnetic compatibility for densely packaged systems as required at mm-wave frequencies. Moreover, its non-dispersive nature makes it a worthy candidate for implementing circuits, antenna and systems at mm-wave frequencies.

1.6 Integration with Existing Technologies: SICL Transitions

As the communication system design is getting more intricate with components fabricated in different technologies, it becomes essential to have a low-loss broadband interconnect between them for efficient functioning of the system. Transition from rectangular waveguide, Substrate Integrated Waveguide (SIW) and Grounded Co-planar Waveguide (GCPW) to SICL have been demonstrated in Fig. 1.8(a). In [Jiang *et al.*, 2014], a waveguide to SICL transition has been designed by etching a coupling aperture on the side of SICL section. A SIW-to-SICL was shown to be employed in SICL fed wideband circularly polarized antenna [Tao *et al.*, 2019]. The SICL-to-GCPW is widely used transition for SICL based devices Liu *et al.* [2019a]. Here, the middle conducting strip of SICL

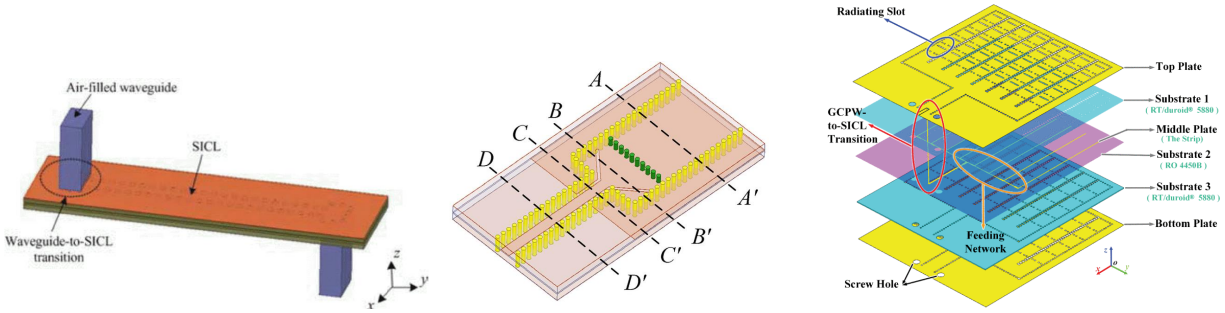


Figure 1.8: Design of various Substrate Integrated Coaxial Line (SICL) Transitions. (a) Waveguide-to-SICL transition [Jiang *et al.*, 2014]. (b) SIW-to-SICL transition [Tao *et al.*, 2019]. (c) GCPW-to-SICL transition [Liu *et al.*, 2019a].

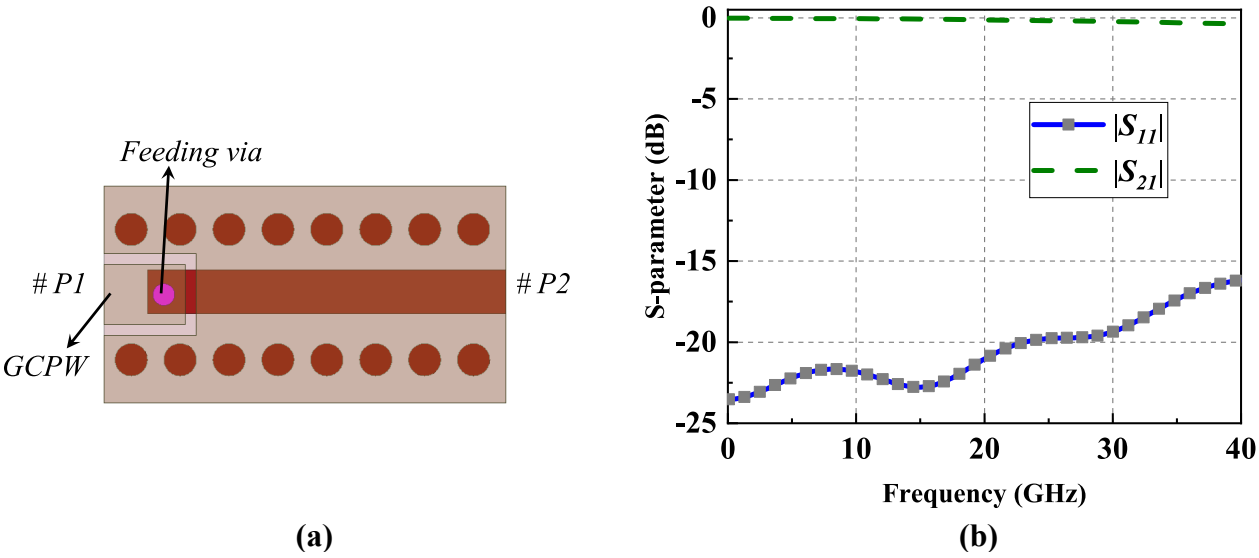


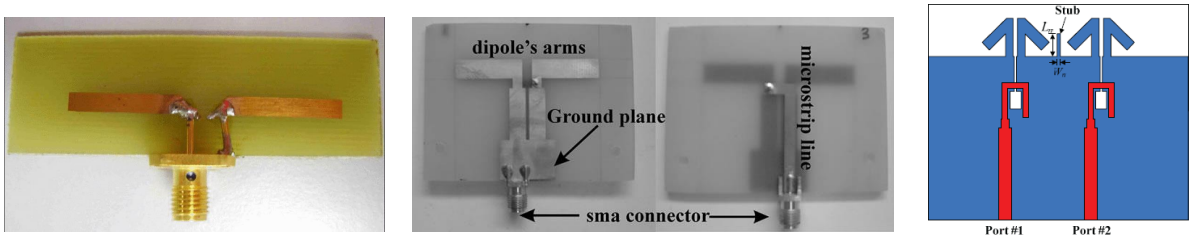
Figure 1.9: Design of Substrate Integrated Coaxial Line (SICL) in (a) isometric view, (b) cross-sectional view and (c) top view. (d) S-parameter performance of the designed SICL transmission line. Dimensions (in mm): H = 1.1, A = 2.4, S = 0.9, D = 0.6

is connected to the signal line of GCPW using a via through the top substrate. One of the most popular transition currently used in SICL technology is the GCPW transitions. One-port SICL-to-GCPW transition has been modelled in full-wave simulator and its S-parameter performance is studied in Fig. 1.9. The SICL-to-GCPW transition is used extensively in this thesis as it provides easy and simplified port for connection of end-launchers to feed the antenna arrays.

1.7 Literature Survey

1.7.1 Dipole Antenna

Wire antennas are one of the oldest, simplest, cheapest and versatile antenna for many applications. For most of the practical applications, half-wavelength dipole antenna (length = $\lambda/2$) are used. Its radiation resistance is 73 Ω, which is close to 50 Ω or 75 Ω impedances that is being used worldwide for system implementation. Its electric and magnetic field equations are given as



(a) (b) (c)

Figure 1.10: Design of printed dipole antennas. (a) Microstrip based dipole ([Jamaluddin *et al.*, 2005]). (b) Microstrip based parallel line feed dipole [Votis and Christofilakis, 2010]. (c) Broadband two-port dipole array [Park and Ta, 2017]

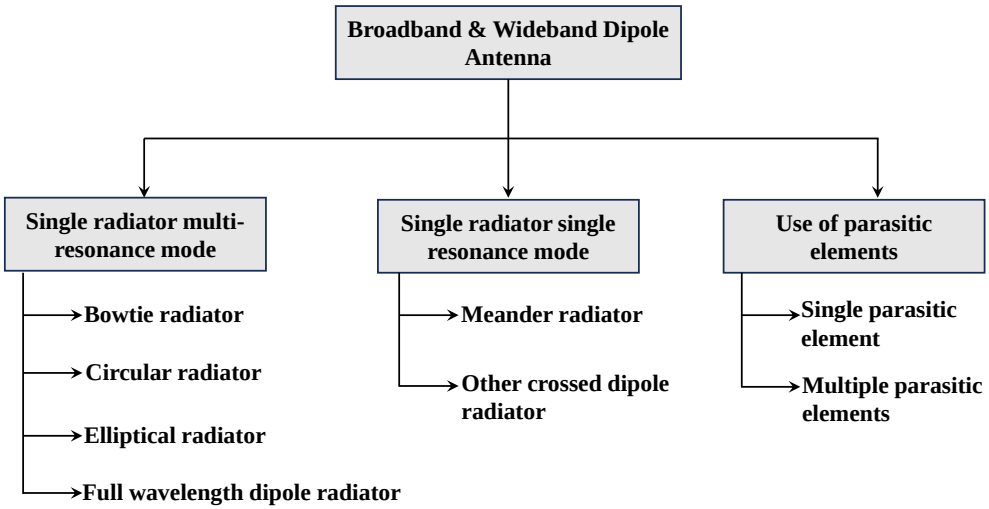


Figure 1.11: Techniques to design broadband & wideband printed dipole antennas.

[Balanis, 2006]:

$$E_\theta \simeq j\eta \frac{I_0 e^{-jkr}}{2\pi r} \left[\frac{cos\left(\frac{\pi}{2} cos\theta\right)}{sin\theta} \right] \tag{1.1}$$

$$H_\phi \simeq j \frac{I_0 e^{-jkr}}{2\pi r} \left[\frac{cos\left(\frac{\pi}{2} cos\theta\right)}{sin\theta} \right] \tag{1.2}$$

For low-profile and planar applications, dipole antennas have been explored much in printed technologies, (mainly microstrip) as shown in Fig. 1.10. Broadband antennas are the requirement for the rapidly expanding systems towards the fifth-generation (5G) communication networks. To exploit the wide bandwidth of the 5G frequency spectrum, RF system needs to be redesigned. Hence, broad-band and multi-band antennas at millimeter wave frequencies are in need. The reported techniques to obtain broadband dipole antennas are shown in Fig. 1.11.

In recent years, dipole antennas have been studied to provide various functionalities for varied applications. Some of these forms of dipole antennas are quasi-Yagi antenna to enhance gain, crossed dipole antennas for dual/ circular polarization, bow-tie antenna for wide bandwidth and Log-periodic antenna for ultra wideband performance.

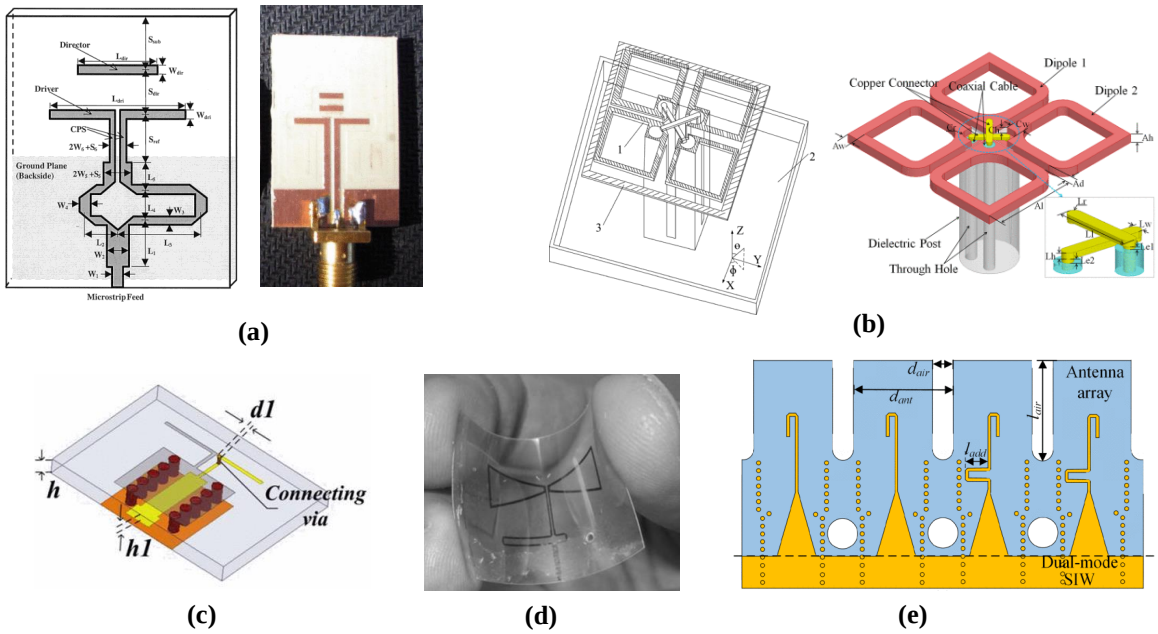


Figure 1.12: (a) Microstrip-fed dipole ([Kaneda *et al.*, 2002]). (b) CPW-fed dipole ([Kan *et al.*, 2007]). (c) SICL fed dipole ([Mukherjee, 2017b]). (d) flexible outline bow-tie antenna ([Durgun *et al.*, 2011]) and (e) SIW fed dual-polarized array ([Lu *et al.*, 2020]).

The Yagi-Uda antenna, initially documented in a journal written in English in 1928 [Pozar, 1997], has been widely employed as an end-fire antenna. The quasi-Yagi antenna generally comprises a driving element, a reflector, and a small number of directors Deal *et al.* [2000]. The directivity of the array is enhanced by increasing the number of directors. However, this enhancement saturates after 10-15 director elements. Therefore, it becomes important to choose number of director elements for desired gain in a defined geometrical footprint. A microstrip fed single-director [Kaneda *et al.*, 2002] and CPW-fed two-director [Kan *et al.*, 2007] quasi-Yagi antenna is shown in Fig. 1.12(a).

Crossed dipole antennas, also called the Turnstile Antennas, are suitable for variety of applications such as dual polarization, circular polarization, single-band and multi-band operations. Crossed dipole antennas are designed by placing two dipole antennas orthogonally within the same proximity as shown in Fig. 1.12(b). Further, feeding the two antennas with in-phase feed results in dual-linear polarization and quadrature-phase feed results in circular polarization respectively. Dual polarized dipole antenna for base station application is designed in [Liu *et al.*, 2013], [Bao *et al.*, 2014] at lower frequencies. At sub-6 GHz frequencies, a dual polarized crossed dipole with dipole arms printed on either side of the substrate fed by microstrip line is designed using Bezies curve to give broadband response [Kobrin *et al.*, 2020]. Much of the work being carried out on crossed dipole antenna adhere to the dual polarized array composed of orthogonal co-located dipole antennas to produce orthogonal polarized beams.

Dipole antenna fed by SICL is explored by researchers in recent years. The two-conductor based SICL transmission line provides ease in providing feed to the dipole antenna. One dipole arm is directly connected to the top layer of SICL while the other dipole arm is connected to middle layer of SICL using a small feeding via. A Substrate Integrated Coaxial Line (SICL) fed simple dipole antenna operating at 24.5 GHz exhibits a bandwidth of 9.6% [Mukherjee, 2017b]. A microstrip-to-CPFN (Co-Planar Feed Network) balun has been used over thin plastic substrate (heat stabilized PEN) to form a modified bow-tie antenna with reduced metallization in [Lin and Tsai, 1997].

Substrate Integrated Waveguide (SIW) fed dipole antenna utilizing balun for out of phase surface currents in the dipole arms exhibits 15.3 % fractional bandwidth for endfire application [Lu *et al.*, 2020]. Polarization diversity is an important factor that avoids multipath fading loss and enhances channel capacity of the wireless systems. Substrate Integrated Coaxial Line (SICL) based dual polarized antennas have been designed for low frequency that utilises SICL slot and printed patch/ monopole as the two radiating antenna elements to give orthogonal linear polarization [Liu *et al.*, 2013], [Sun *et al.*, 2020a], [Gao and Song, 2019], [Wang *et al.*, 2019].

1.7.2 Cavity Backed Slot Antenna

The cavity backed slot antenna is often considered as a top choice for flush mounted antennas or flat plate slot array antennas, particularly in aircraft, satellite communication, and military applications. These antennas are constructed by integrating a metallic cavity behind the slot, which is typically excited by an open-ended microstrip line. The height of the cavity is often selected to be one fourth of the guided wavelength in order to ensure that the reflected wave from the backside cavity wall combines in phase with the forward radiated field above the cavity. Fig. 1.13(a) [Hirokawa *et al.*, 1989] displays the isometric perspective of the cavity backed slot antenna. The slot antenna is realized by creating an opening in an infinitely large conducting surface, which also acts as the upper boundary of the cavity. The slot is excited by a microstrip line positioned on the upper surface of the dielectric substrate. The radiation pattern of the cavity backed slot antenna is seen in Fig. 1.13(b) and (c). Compared to the bidirectional radiation pattern of the slot antenna, the use of a cavity backing allows for the implementation of a unidirectional radiation pattern with a larger front-to-back ratio. In addition to its unidirectional radiation properties, the utilization of a cavity also aids in mitigating the mutual coupling effect when employing antenna arrays. Additionally, these antennas may be easily and securely fixed directly into the body of the vehicle or aircraft. Therefore, these antennas are widely used in aviation phased array systems, satellite communications, and vehicle applications, among others.

The shielded technologies have facilitated the design of cavity in planar technologies. One of the widely used cavity based antennas are SIW cavity backed slot antennas where a slot antenna is backed by SIW cavity to exhibit unidirectional radiation pattern [Luo *et al.*, 2008b]. The slot antenna is placed at the center of the SIW cavity in a planar substrate. The cavity is fed by 50 Ω microstrip line which excites TE_{120} mode in the cavity. The slot placed at the top plate of the cavity disturbs the surface current distribution of TE_{120} mode which helps to excite it to radiate into free space. The antenna geometry and its response is shown in Fig. 1.14. The antenna exhibits single band resonance with unidirectional radiation pattern and high gain, owing to the narrow band SIW TE mode. To have bandwidth improvement, method of staggered tuning using different cavity modes and removal of back substrate are some of the techniques utilized in the SIW cavity.

Substrate Integrated Coaxial Line (SICL) is a two-conductor transmission line that enables wideband dominant TEM mode. Proper designing and utilization of this mode enables to have wideband performance in the SICL based antenna designs. Few cavity backed antenna configurations based on SICL cavity have been studied for high gain applications. SICL based cavity is formed in [Hou *et al.*, 2018b] by etching the top plate with four radiation patches on the top metallic layer, which are connected to the I-shaped feed network on the middle metallic layer using blind vias as shown in Fig. 1.15(a). Further, an antenna array is formed with 1 $\times$ 4 cavity-backed patch antenna array, a T-junction power divider based on SICL that produces -10 dB impedance bandwidth of 11.44 GHz (25.42%) with a gain of 15.8 dBi at 45 GHz. Another SICL-fed dual-polarized antenna array has been designed to demonstrate 2 GHz bandwidth (24.5 - 26.5 GHz) with high isolation below 23 dB for the entire bandwidth [Filgueiras and Cerqueira Sodr, 2022]. The proposed array produces a gain of 7.4 dBi gain which is further utilized for MIMO application. 5 $\times$ 8 transverse slots antenna array is designed in [Liu *et al.*, 2019b] to have suppressed sidelobe levels (SLLs) that

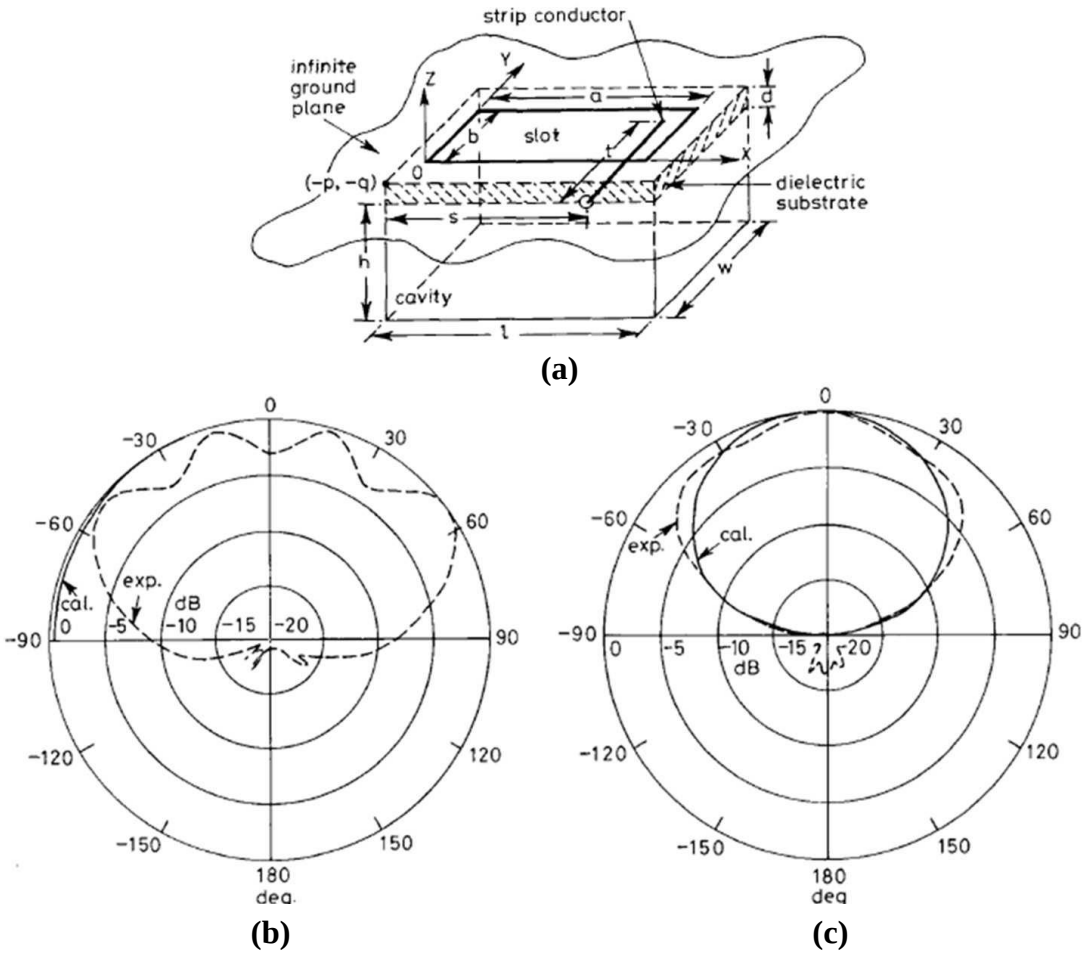


Figure 1.13: (a) Cavity backed slot antenna; (b) E plane radiation pattern; (c) H plane radiation pattern ([Hirokawa *et al.*, 1989])

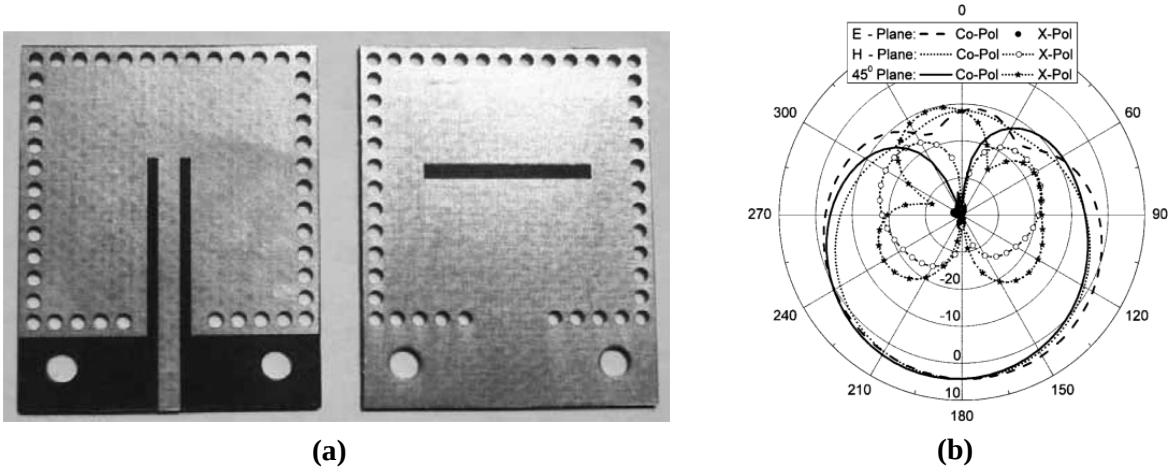


Figure 1.14: (a) Photograph and (b) radiation patterns in different cut-planes at 10 GHz of the proposed SIW cavity backed planar slot antenna. ([Luo *et al.*, 2008a])

exhibits a 3.57 % bandwidth at 34.5 GHz with a peak broadside gain of 18.82 dBi. The SLL pat-

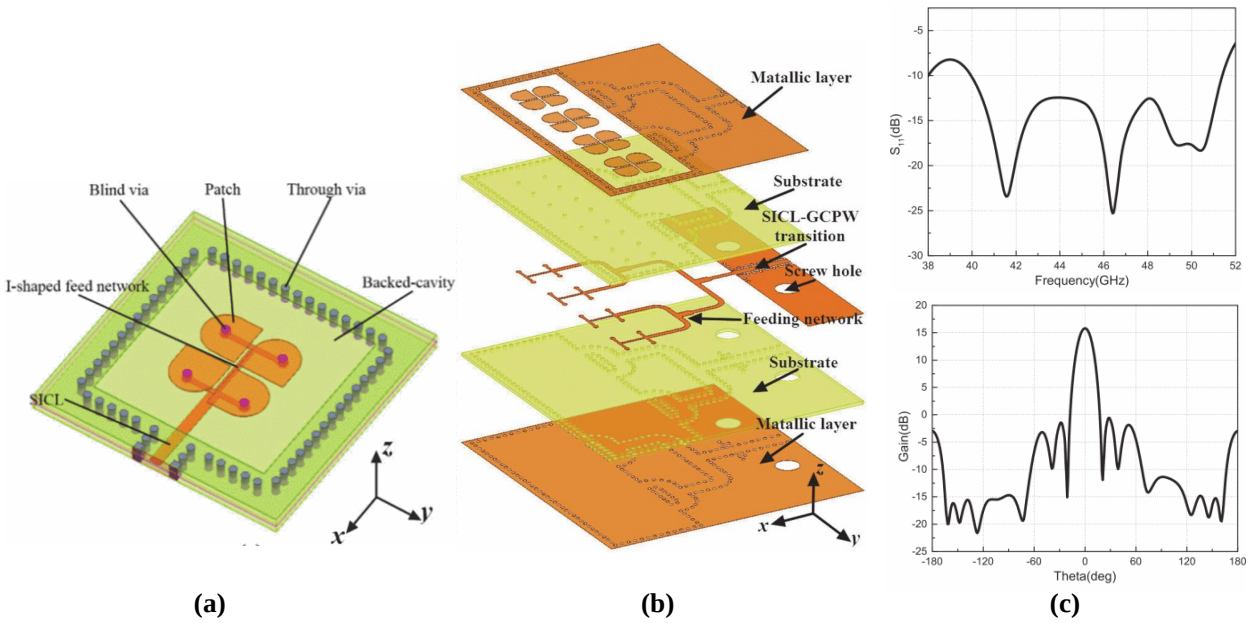


Figure 1.15: (a) Single element, (b) 1 × 4 array of the Q-band SICL based cavity backed slot antenna. (c) Simulated performance and radiation patterns. ([Hou *et al.*, 2018a])

tern in both E-plane and H-plane of -18.4 and -19.2 dB respectively is reported. Another 5 × 6 inclined-slot array with a 45° inclined linear polarization (LP) is designed for Ka-band [Liu *et al.*, 2019b]. The proposed array exhibits peak gain of 17.09 dBi at 34.5 GHz and -10 dB impedance bandwidth of 910 MHz with sidelobe levels in E- and H-plane of -19.6 and -18.0 dB respectively.

1.8 Motivation and Scope of this Thesis

The Substrate Integrated Coaxial Line (SICL) antenna systems have huge potential for various microwave and millimeter wave applications. These systems offer a lightweight and conformal design, making them suitable for replacing bulky non-planar metallic cavity and waveguide antennas. Radio communication at high frequencies, especially 5G FR2 band, encapsulates the application of 5G millimeter wave, radar communication and customer premises equipment (CPE). The well-known microstrip technology becomes lossy at high frequency due to the generation of surface waves and radiation losses on the other hand. The bounded Substrate Integrated Waveguide (SIW) technology supports narrowband single mode operation. Substrate Integrated Coaxial Line (SICL) is an emerging and promising candidate with self-shielded structure that removes the drawbacks of these existing technologies. Recently, SICL has attracted the interest of researchers and led to antenna designs for millimeter (mm) wave application with SICL.

Due to the exponentially growing traffic over the last few decades, the lower frequency bands have become overcrowded. Hence, there is a steady push towards the higher frequency spectrum. The next generation wireless access system (5G) is a plausible solution capable to support the demands of increasing data rates and accommodate the constantly increasing traffic by exploiting larger bandwidth. As discussed previously, a lot of recent advancements and updation is currently being carried out for 5G technology such as spectrum management, resource allocation, etc. There is a constant search for new techniques and technologies to harness the wide spectrum provided by 5G mm-wave bands. Specifications are being laid down by 3GPP working group in accordance with IMT-2020 for distribution of spectrum around the world. WRC-19 have identified FR2 bands

beyond 24 GHz for outdoor mm wave applications. Highest interest of 3GPP has been in the 5G mm wave New Radio (NR) bands around 28 GHz, namely n257 (26.5 to 29.5 GHz), n258 (24.25 to 27.5 GHz) and n261 (27.5 to 28.35 GHz).

The motivation of this thesis is to design and develop antenna and arrays using the novel Substrate Integrated Coaxial Line (SICL) technology with multi-functional performance in the 5G mm wave FR2 bands beyond 24 GHz for its worldwide application. As discussed in Sec. 1.8, several studies on SICL based antennas have been reported in recent years. However, limited works have been found to design multi-band antenna systems based on SICL technology to meet multifunctional wireless radio communication. Also, there is a call to design novel antennas to fit in the limited footprint of a mm wave circuit for dense system integration for 5G. In this thesis, a detailed research have been carried out to design high gain antennas with broad bandwidth to meet the requirement at millimeter (mm) wave frequencies. Dense 5G deployment requires high gain antenna arrays in a compact footprint. Flush mounted cavity backed slot antenna (CBSA) is another suitable candidate that is compact and occupies less space. Moreover to have a multifunctional system, dual band antennas need to be developed for 5G FR2 mm wave frequencies. Though the Front-to-Back ratio (FTBR) of CBSA is high, still it is required to improve over FTBR characteristics to have highly directive beam in the boresight direction. Design of dipole antennas can also be explored with SICL feeding network. Broadband and wideband antennas needs to be developed to meet the requirements of FR2 NR bands. To have practical application, these antennas need to validated with the design of arrays to have high gain. Broadband beam switching, pattern re-configurability and polarization diversity are demanded by the 5G standards for mm-wave spectrum. In order to avoid multipath fading loss and enhance the channel capacity, SICL based MIMO designs would provide improvement in isolation parameter and MIMO metrices to provide coverage over a large area.

According to the Friss transmission line formulae, the path loss at high frequencies (mm wave) become prominent as compared to microwave frequencies. Hence, the challenge exists for designing the RF front end, especially antennas at millimeter wave frequencies with high gain. A substantial amount of this research is focused on developing high-gain antenna systems operating in the FR2 band matching the specifications of 3GPP. Radio communication at such frequencies encapsulates the application of 5G millimeter wave, radar communication and customer premises equipment (CPE). The well-known challenge with arrays is to reduce the mutual coupling between antenna elements. SICL offers a shielded environment to the feeding network that eliminates surface waves and takes care of mutual coupling. Decoupling networks, EBGs or inclusion of band-pass filters is not required in SICL based arrays which ultimately reduces the size of the design and makes the array compact. Another challenge from designers perspective in designing high-gain arrays is to accommodate array in a small footprint for dense 5G systems. Novel configurations in crossed dipole antenna arrays may be proposed that achieves wide bandwidth and high gain while maintaining small footprint. A 2x4 SICL based slot antenna array may be designed at 28 GHz with a unidirectional broadside gain of 10.6 dBi. Further, a dual beam 6x4 SICL slot antenna array exhibiting a bidirectional gain of 10 dBi at 25.16 GHz may be designed using double sided C-shaped slot. A SICL based switching board with low insertion loss has been designed to support operation from 24 - 32 GHz utilizing a SPDT RF swtich. This board has been utilized to feed antenna array to achieve dual polarization over a wide FR2 n257 band. To establish a satisfactory link of the end users with the access point, 360° beam coverage is essential. High gain antenna arrays generally makes the beam directive, decreasing the beamwidth and thereby restricting its coverage. Hence, MIMO antenna arrays (for upcoming 5G/6G) with high isolation and spatial diversity performance is required. A MIMO array with novel feed line is designed that supports simultaneous 10/28 GHz transmission for futuristic 5G & beyond communication may be explored. These MIMO arrays may provide spatial and polarization diversity over wide n257 band. A simultaneous dual beam in different directions with low sidelobe levels may be designed for making the 5G communication

system more reliable and robust.

This thesis work has emphasizes on the transformative potential of antenna design with SICL technology in shaping the future of communication.

1.9 Organisation of the Thesis

The thesis is divided into six chapters with **Chapter-1** as introduction, where the basics of Substrate Integrated Coaxial Line (SICL) along with its applications in antenna systems has been discussed. First, the overview of 5G wireless access system with its use cases and specifications have been discussed. Next, a novel technology SICL has been has been introduced. To have integration with existing technologies, SICL transitions are discussed. Later, the design mechanism of two popular antennas namely, dipole and cavity backed slot antenna is discussed. A brief literature survey on the two antennas is presented. Finally, the motivation and scope of this thesis has also been mentioned here.

In **Chapter-2**, a detailed discussion on designing SICL based broadband & wideband antennas are presented. This chapter proposes few SICL based dipole antenna designs with different approaches to enhance the bandwidth for 5G millimeter wave frequencies. A SICL-fed quasi-Yagi antenna is designed to have broad bandwidth and high gain. Next, a parasitic dipole antenna is utilized along with a dipole antenna to enhance the bandwidth of the antenna. Finally, to have wideband performance, a Bow-Tie antenna fed by SICL is presented in FR2 mm wave band. The results of the proposed design are also presented which exhibits attractive performance encouraging its utilization for developing antenna arrays.

Chapter-3 is devoted to dual polarized antennas. This chapter presents three different dual polarized antennas. Three different design techniques are proposed to obtain polarization diversity in SICL fed endfire and broadside dipole antennas. Firstly, a dual polarized dipole antenna is obtained using orthogonal antenna on either side of the SICL substrate with a common dipole arm in the middle plate of SICL. Dual linear polarization is achieved in this design by controlling the excitation of the two antennas using RF switch. Second dual polarized antenna proposed in this chapter, produces polarization diversity by controlling the excitation of the two dipole antennas placed on the same side of the substrate. An endfire array of the proposed antenna is designed by stacking 4 layers of the proposed antenna configuration. Lastly, a dual polarization in a dual-frequency antenna is designed using a dipole antenna and folded patch antenna fed by the same SICL feed section. The bottom ground plate of the SICL below the antennas is extended to obtain broadside beam.

Chapter-4 deals with the design of multifunctional SICL cavity backed slot antenna (CBSA). A SICL cavity is formed and its resonating modes are characterized. Further, a slot is etched on the proposed SICL cavity to design SICL based CBSA. To appreciate the performance of SICL based design, a comparative study has been made between SIW & SICL CBSA. To have dual band operation, a compact dual band SICL CBSA with high Front-to-Back ratio (FTBR) is presented. Further, a novel technique to improve FTBR in SICL CBSA is proposed and studied analytically. Finally a novel half mode SICL (HMSICL) antenna is proposed in much compact footprint, which is utilized in designing a dual beam antenna array for Full-duplex application.

Chapter-5 deals with designing of high-gain antenna arrays for 5G mm wave applications. It begins with designing slot antenna arrays. Firstly, a 2 x 4 C-shaped slot antenna array is proposed for unidirectional radiation characteristics. Following the same analogy, a bi-directional 6 x 4 slot antenna array is proposed using C-shaped slots on both the top/bottom plate of the SICL transmission line. Next, in order to have compact linear arrangement of dipole antennas in

a small footprint, a novel technique to implement crossed dipole antenna in SICL technology is proposed that exhibits wideband performance. A SPDT RF switch based novel SICL switching board is designed, which is utilised for dual polarization and simultaneous dual beam application over wide n257 band. Further, stacked configuration of the HMSICL antenna is utilized to improve the bandwidth of the proposed HMSICL array.

Chapter-6 is devoted to Multiple-Input Multiple-Output (MIMO) antenna array to provide coverage over large geographical area. Three designs of MIMO antenna configurations are explored in SICL that exhibits high isolation over the entire operational bandwidth. Another novel configuration of crossed dipole antenna is proposed for wideband endfire MIMO application. A 4 x 4 MIMO antenna configuration using novel transmission line is designed that enables simultaneous 5G/ 6G operation using a single port. Lastly, a 8 x 8 MIMO antenna is designed for both spatial and polarization diversity in a single design.

Finally **Chapter-7** concludes the thesis and also discusses future scope of the thesis.