1
Introduction

The upcoming wireless standards has bought new design requirements for communication components to support high data transmission rate. Wireless communication is about to experience tremendous utilization with emergence of the new 5G communication. In the recent times, to handle the increasing number of wireless service users, the emerging fifth generation (5G) communication has demonstrated potential to support diverse services owing to its high data rate and bandwidth. The stringent requirements of 5G would be testing the designers to produce planar components to accommodate its FR-1 (Sub-6 GHz) & FR-2 (28 GHz) band simultaneously. Furthermore, the evident need for low-loss transmission media at higher frequency bands in 5G communication motivates the demand for a new compact planar guiding media. For enhanced functionality of the system, hybrid integration of various transmission lines will be necessary and is an important aspect to be considered. Moreover, need for high speed and high capacity communication is constantly pushing towards design and development of wideband microwave and millimeter-wave components. Use of such microwave/millimeter-wave components operating for a wide contiguous channel that can serve multiple bands simultaneously aids in overall size and cost reduction. To fulfill the present day needs, millimeter-wave frequency bands are being utilized for high speed wireless access. There has been a steady raise in deploying newer communication standards in millimeter-wave range such as, fifth generation cellular telephony [15], IEEE 802.11 ad wireless local area network (WLAN) [16], passive millimeter-wave imaging [17] and many more. The challenges in circuit design grow manifold with increase in operating frequency. The substrate loss, ohmic loss and radiation loss dominate at high frequency if the circuit design is not designed cautiously. Also the widespread utilization of communication services pushes for design and development of transceivers in a small form factor [18]. Another important band that needs special attention in design of RF-front end is the K_u-band [19] which is utilized for satellite and RADAR communication and imposes stringent requirement in terms of insertion loss, size and design flexibility. Although millimeter-wave bands are currently being tried for 5G, K_u-band has emerged as an prospective frequency band [20] for 5G trials by academic and research organizations due to low loss and ability to support high data rate. Moreover, *Ku*-band is a preferred choice to host satellite (very small aperture terminals) and RADAR communication [19] which requires light weight systems for radars and sensing applications. Researchers are investigating design of high-performance transceiver units for mobile satellite reception in these bands as they are advantageous due to shorter wavelength (smaller size) and availability of wide bandwidth. Furthermore, an efficient system design requires integration of active circuitry with passive components on the same board to maintain a compact size. Such stringent requirement for design of components for the rapidly evolving system requires a new guiding media that supports wide bandwidth in small footprint and low insertion loss.

1.1 BRIEF REVIEW OF EXISTING TECHNOLOGIES FOR DEVELOPMENT OF MODERN RF-FRONT END

Novel technologies in planar form have emerged for efficient design of microwave/millimeter-wave circuits. Waveguides are very popular for operating at high frequency as they exhibit low loss and excellent stability to environmental variation. Waveguides

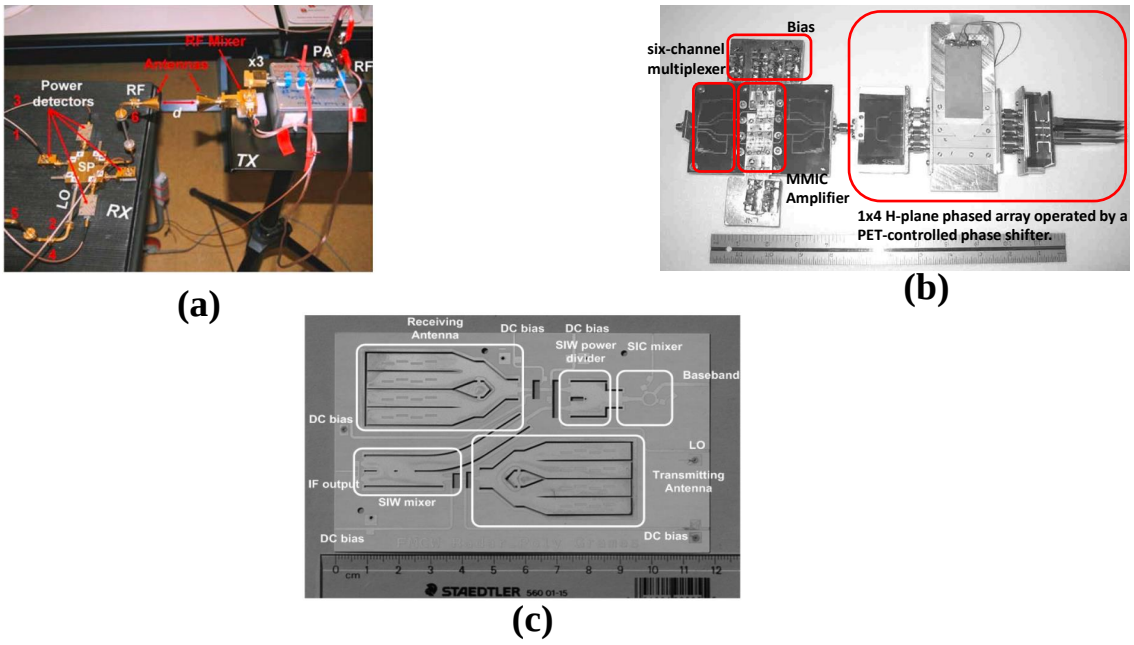

Figure 1.1 : Review of various technologies to implement integrated system (a) experimental V-band direct-conversion receiver test bench (Courtesy: C. Hannachi, E. Moldovan, S. Boumaiza and S. O. Tatu, "V-band Multi-port Waveguide Direct-Conversion Receiver: Design and M-ary PSK Demodulation Results," 2018 18th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM), 2018, pp. 1-2. [1]. (b) Microstrip technology based transceiver with beam scanning capability (Courtesy: Seungpyo Hong, Sang-Gyu Kim, M. R. Coutant, C. T. Rodenbeck and Kai Chang, "A multiband, compact, and full-duplex beam scanning antenna transceiver system operating from 10 to 35 GHz," in IEEE Transactions on Antennas and Propagation, vol. 54, no. 2, pp. 359-367, Feb. 2006 [2] (c) SIW based FMCW Radar Front-End System (Courtesy: Z. Li and K. Wu, "24GHz FMCW Radar Front-End System on Substrate," 2007 IEEE Radio and Wireless Symposium, 2007, pp. 233-236) [3]

based systems are popularly deployed in satellite communication since power is a very crucial resource and losses are expected to be minimal. An experimental test bench of multi-port V-band waveguide direct-conversion receiver is shown in Fig. Fig. 1.1 (a). Typically waveguides are heavy due to their built material making them unsuitable for implementation in hand-held devices. Moreover, as waveguide systems are implemented at lower frequency they become extremely bulky and also demonstrate narrow-bandwidth due to their high-quality factor. A full-duplex beam scanning antenna Transceiver System operating from 10 GHz to 35 GHz is shown in Fig. 1.1 (b). This transceiver developed in microstrip technology enjoys the compact and planar form factor which is not present in waveguides. It is observed that the semi-open structure causes severe parasitic coupling and has high conductor loss at millimeter-wave frequencies due to concentration of current density in the edges of microstrip line and suffers from radiation loss and surface-wave loss. Special attention is required for packaging of microstrip technology based circuits at high frequency and often a metal box is used to create a shielded environment. But such packaging ultimately increases the overall weight of the device. Gold plated microstrip lines has been used in transceiver shown in Fig. 1.1 (b) to combat with the losses at millimeter-wave bands. However, such gold based microstrip line is not commercial viable for mass production and widespread utilization. In Fig. 1.1 (c) an FMCW radar front-end system integrated on one single substrate has been demonstrated using substrate integrated waveguide technology (SIW). Substrate integrated waveguide (SIW) has emerged as one of

the sought-after self-shielded planar guiding media with relatively less fabrication complexity to design microwave and millimeter-wave circuits. SIW incorporates non-planar waveguide structures in a planar substrate by the use of rows of metallic vias that implement the sidewall of the waveguide-based circuits in planar substrates. Due to its planar implementation it is suitable for integration with various front-end components of different technologies. Furthermore, SIW has lower sensitivity to manufacturing tolerance making it highly suitable for high frequency bands. However, since SIW is a single conductor system many of the active circuits in the system shown in 1.1 (c) have been designed in microstrip technology and they ultimately suffer from high conductor loss, surface wave loss and radiation loss. In [23], planar counterpart of waveguide has been extensively utilized to develop various microwave circuits and antennas. SIW occupies larger area than TEM based circuits and cannot offer broad-bandwidth due to inherent narrow mono-mode bandwidth. These gaps in the existing technologies motivates us to explore new technologies to design compact, low-loss, wideband planar transmission lines. Need for new technology to support mm-wave communication is clearly understood from the shortcomings of the currently used planar technologies:

1. Microstrip: Microstrip technology has low profile and good integration ability, but is not preferable for operation in millimeter frequency range due to radiation loss at high frequency. It also suffers from surface wave loss and high conductor loss at high frequency of operation. Gold plated microstrip line are used to combat with the losses but usage of such expensive material makes it commercially unviable.

2. Coplanar Waveguide (CPW): Surface-wave losses are dominant for CPW transmission lines at millimeter-wave communication.

3. Stripline: At mm-wave range components are very small and close to each other, stripline fails to provide the necessary lateral shielding.

4. Substrate Integrated Waveguide (SIW): Occupies larger footprint than TEM based technologies and has narrow mono-mode bandwidth but is a suitable technology for system implementation.

An interesting solution to this problem was provided by substrate integrated coaxial line (SICL) technology having broad-bandwidth owing to the unimodal TEM based transmission in a compact form factor. SICL is the printed form of traditional coaxial line which is designed by laterally limiting a metallic strip by a pair of copper deposited vias on both sides with metallic plates enclosing it as shown in 1.2. The self-shielded and self-packaged SICL technology is expected to be an attractive candidate to design circuits for RF-front end. Utilization of SICL technology

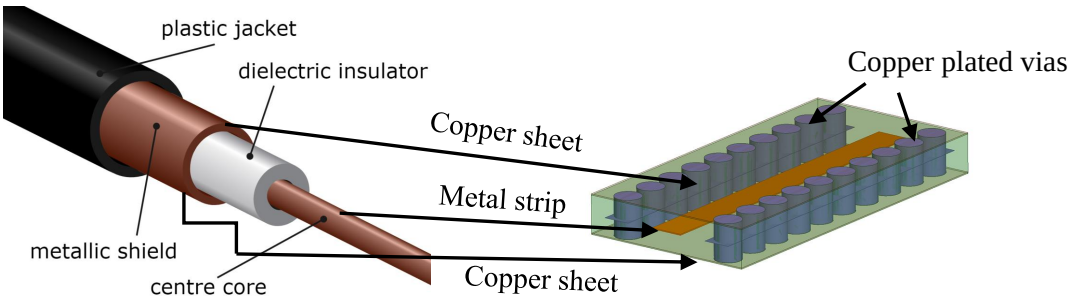

Figure 1.2 : Representation of structural similarity between a conventional coaxial line and a substrate integrated coaxial line (SICL)

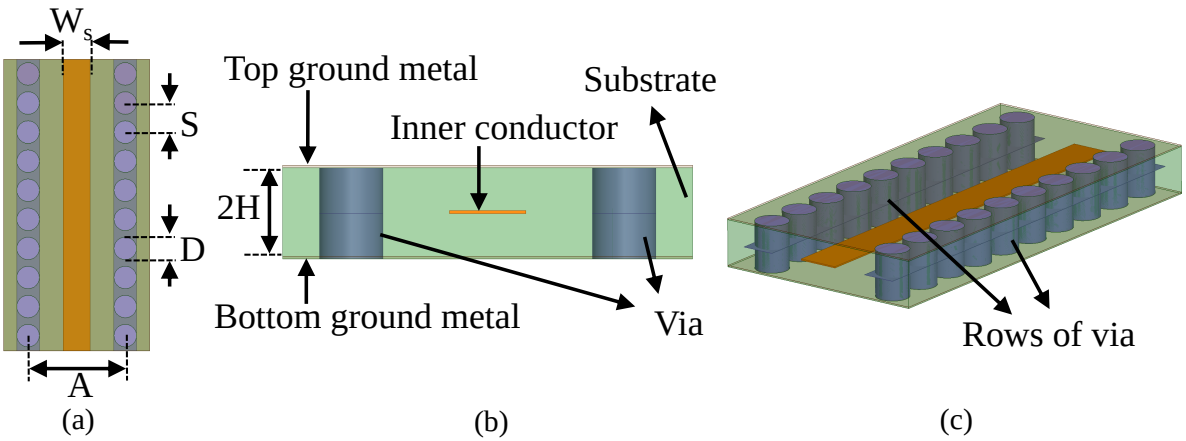

Figure 1.3 : Design of substrate integrated coaxial line (a) Top view, (b) cross-sectional view and (c) isometric view, of a substrate integrated coaxial line

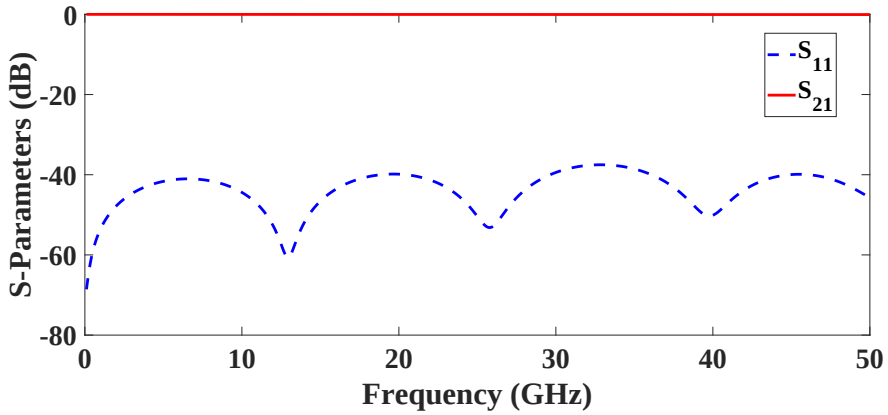

Figure 1.4 : S-Parameters of the Substrate Integrated Coaxial Line with dimensions: A = 2.5mm, S = 0.9mm, D = 0.6mm, 2H = 1mm.

in antennas and antenna array reduces the feed network losses and can reduce the mutual coupling between elements of array. Further, the bias lines and intermediate connection between transistor and matching network of active circuits when designed in the completely shielded SICL offers low-loss and excellent signal integrity. Further design of passive components such as filters, couplers using the high Q, low-loss resonator facilitates design in compact size with wide-monomode TEM based characteristics. The planar and seamless integration offered by SICL technology makes it a highly seeked candidate for microwave/ millimeter-wave overall transceiver system design. A substrate integrated coaxial line section is fabricated by sandwiching a conducting strip between a pair of low loss substrates. This configuration is bounded by two rows of metallic vias connecting the top and bottom plane with a metallic sheet enforced through the vias to enhance the coaxial nature of SICL. The entire configuration is delimited by rows of metallized-vias on both its sides. The diameter of via is *D*, spacing between vias is *S* and distance between rows of vias is *A*. In Fig. 1.3 shows the top and cross-sectional view of SICL is presented. Proper choice of the parameters namely *D*, *A* and *S* enables the designer to ensure single-mode TEM propagation through the entire range of frequencies up to the next higher order mode (TE_{10}).

The S-parameters in Fig. 1.4 confirm the wide-band propagation of single mode from DC to

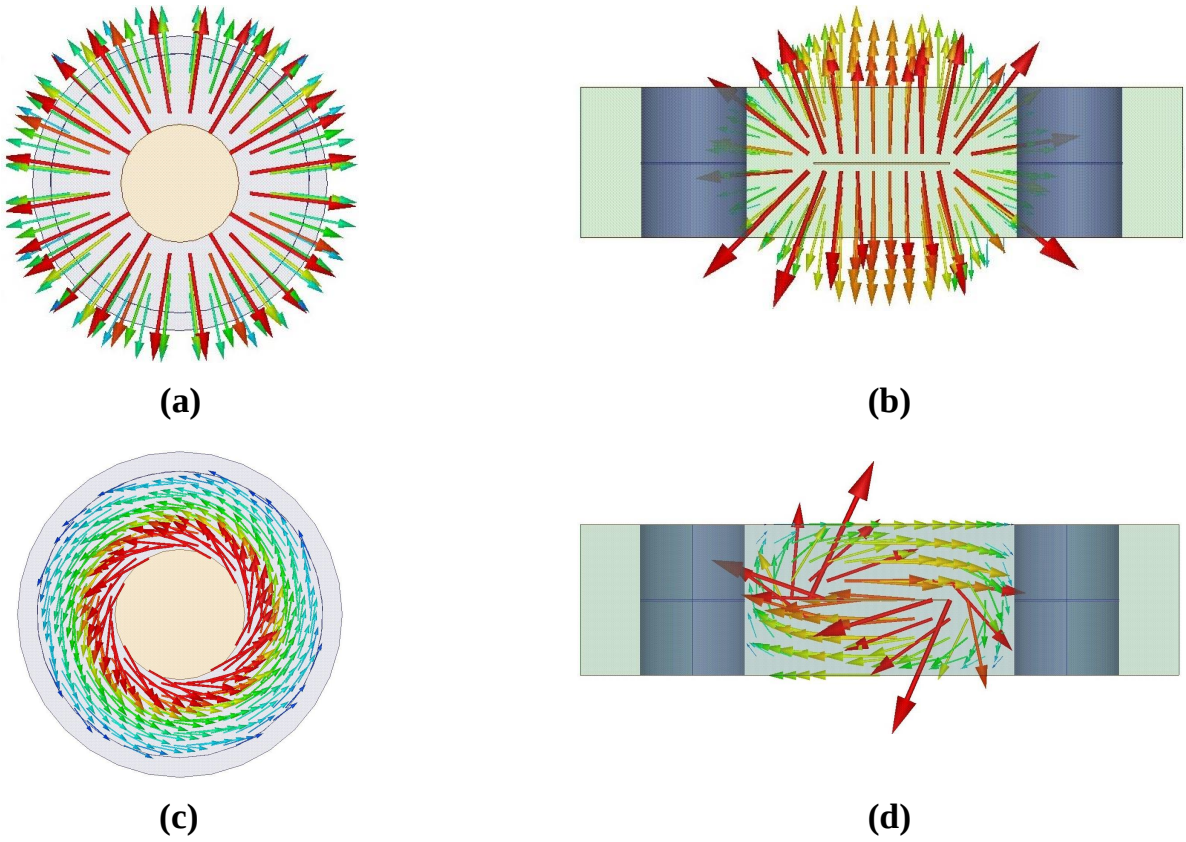

Figure 1.5 : Vector electric field distribution in (a) Coaxial Line (b) SICL, vector magnetic field distribution for (c) Coaxial Line (d) SICL

50 GHz with very low insertion insertion loss using High frequency structural (HFSS) full-wave simulation. By observing the coaxial like radially outward directed E-field vector and concentric H-field of conventional coaxial line & SICL transmission line in Fig. 1.5, it is confirmed that the SICL is indeed the planar form of traditional coaxial line. The advantages of SICL technology are as follows

1. **Unimodal:** Supports wide-bandwidth over single mode of propagation.
2. **Non dispersive:** All frequencies travel with same group velocity
3. **Shielded:** At mm-wave range components are very small and close to each other (densely integrated), hence shielding becomes very important.
4. **Planar:** Makes it easily integrable with other technologies.
5. **Low loss:** The self-shielded and self-packaged structure of SICL aids in low loss.
6. **Ease of Fabrication:** Standard PCB fabrication

Whereas, SICL provides excellent electromagnetic compatibility for densely packaged systems, and the non-dispersive nature of SICL makes it a worthy candidate for implementation of circuits at millimeter-wave frequency. In the recent time, SICL based transitions [24, 25, 26], filters [27, 28], antennas [6, 29], balun [7], oscillator [30] have been investigated. An SICL based high speed data transmission system [18] was devised and tested to demonstrate a data rate of 30 Gb/s per channel

to show its usefulness in practical systems.

1.2 TRANSITIONS TO SICL TRANSMISSION LINE

Several novel technologies have surfaced in the recent times to design millimeter wave circuit in planar form. As the system design is getting more intricate with components fabricated in different technologies, it is essential to have a low-loss broadband interconnect between them for effective working of the system. This kind of integration provides superior performance due to the increased functionality of the system. SICL also referred as fenced stripline [10], [31] supports low loss at millimeter-wave frequency and prohibits propagation of undesired parallel plate mode. The wideband TEM mode of wave propagation in SICL can simultaneously support the operating bands of upcoming 5G communication and also provide backward compatibility to 3G/4G spectrum. Whereas, SICL provides excellent electromagnetic compatibility for densely packaged systems, and the non-dispersive nature of SICL makes it a worthy candidate for implementation of circuits at millimeter-wave frequency. Transition from rectangular waveguide, substrate integrated waveguide, and grounded coplanar waveguide to SICL technology has been demonstrated in Fig. 1.6 A SIW-to-SICL transition was shown to be employed in SICL fed wideband circularly polarized antenna in [35]. The SICL to Grounded-coplanar waveguide line is a widely used transition for SICL based devices [7]-[37]. The inner conductor of SICL is electrically connected to the top ground plane using a metallic via-hole. In [4], a waveguide to SICL transition has been designed by etching a coupling aperture on the side of SICL section. A SICL to waveguide transition has been developed [38] using a mettalic pin, substrate filled cavity and a coupling aperture for frequencies covering 70 GHz to 86 GHz. A novel methodology to interconnect substrate integrated suspended line with coplanar waveguide is shown in [39]. In [40] and [41], a coaxial to SICL transition has been reported. A novel rectangular waveguide to SICL transition is proposed in [38] to act as a four way power divider to feed a circularly polarized

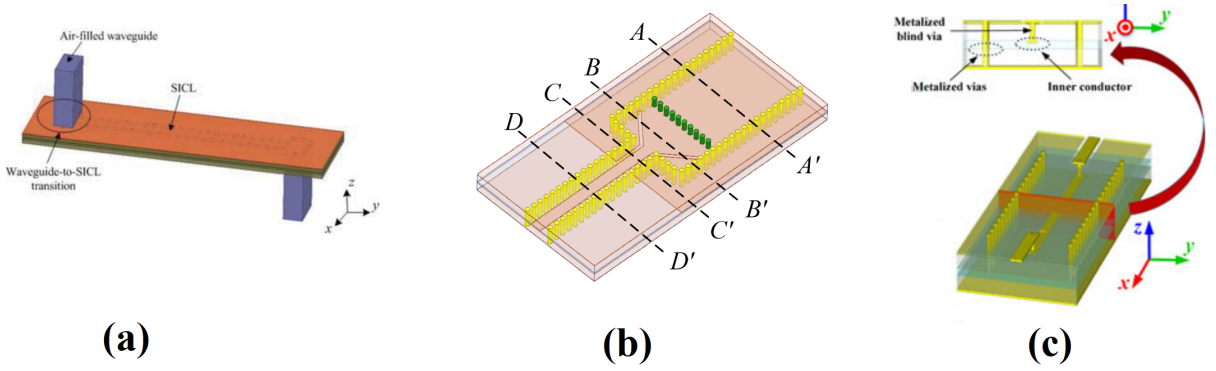

Figure 1.6 : Various transitions to SICL technology (a) Waveguide to SICL excitation (Courtesy: M. Jiang, W. Hong, Y. Zhang and H. Zhou, "A broadband waveguide to substrate integrated coaxial line (SICL) transition for W-band applications," 2014 Asia-Pacific Microwave Conference, 2014, pp. 70-72) [4]. (b) Utilization of SIW to feed an SICL based transmission line (Courtesy: Tao, M.C., Wu, Y.W., Jiang, Z. and Hao, Z.C.," in IET Microwaves, Antennas & Propagation, vol. 13, no. 11, pp. 1764 – 1767, September 2019) [5] (c) A grounded coplanar waveguide to SICL transition using plated blind via (Courtesy: Bing Liu, Ke Xing, Lei Wu, Zijun Guo, Xiangyun Wei, Yu Ma, and Renrong Zhao, "A Novel Slot Array Antenna With a Substrate-Integrated Coaxial Line Technique," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1743-1746, 2017) [6]

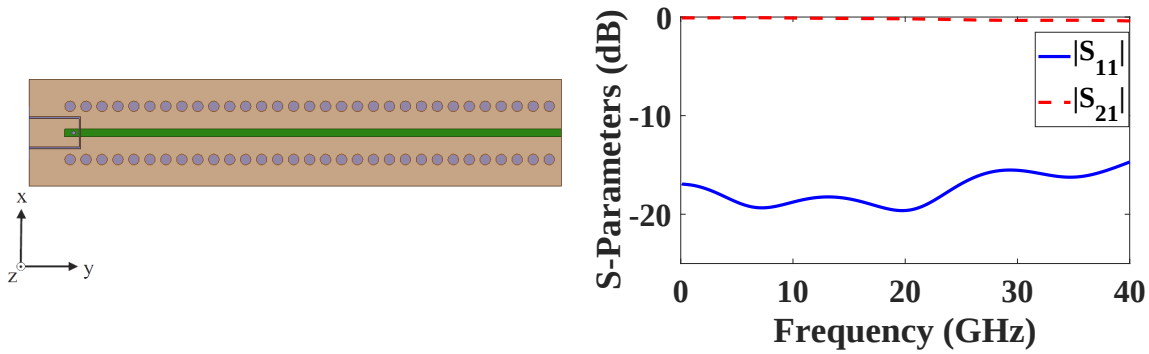

Figure 1.7 : S-Parameters of one-port SICL to GCPW transition with 1.2mm substrate thickness

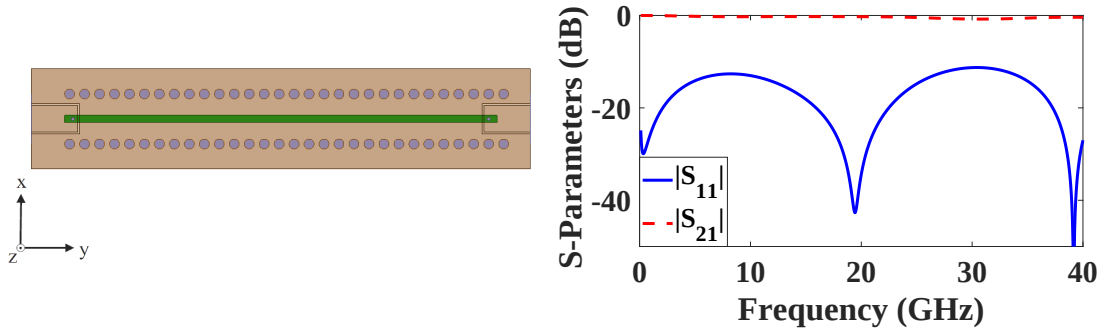

Figure 1.8 : S-Parameters of two-port SICL to GCPW transition with 1.2mm substrate thickness

antenna array in E-band. One of the most popular transition currently used in SICL technology is the grounded coplanar waveguide (GCPW) transition [24], [12] in which a plated via connects the central conductor of SICL to signal line of CPW. One-port and back to back SICL to GCPW transition has been modeled in full-wave simulator its S-parameters are studied in Fig. 1.7 and Fig. 1.8, respectively. In [24], SICL to CPW transition fabricated in low temperature co-fired ceramic (LTCC) technology is shown to operate up to 40 GHz with insertion loss less than 2 dB in the entire 10 dB return loss bandwidth. A SICL to conductor backed CPW transition (CBCPW) [12] devised in standard PCB technology demonstrated better than 10 dB return loss & 1.72 dB insertion loss in DC-13 GHz band. Design and working of an SIW to SICL transition has been verified in [42] for 6.7 GHz to 7.42 GHz band. In [43], integration of substrate integrated waveguide (SIW) filter with a non-resonant SICL node is experimentally validated. The usage of CBCPW to SICL transition is discouraged for ultra-thin substrates as the width of the CBCPW signal line is considerably small & soldering the coaxial connector becomes challenging.

1.2.1 Need for DC Isolated Transition

One of the challenges in the design of system is of integration passive and active circuits. It is very important to isolate DC bias circuitry required for active circuit from the system to maintain the intended operation of components on board. To achieve compact size, microwave components with inbuilt DC isolation have been explored in the past. Coupled lines serve as a popular choice to enhance the bandwidth of a quadrature hybrid [44] and power divider [45] with simultaneous DC blocking capability. Further, integrating coupled line in design of impedance transformers [46] for input/output matching network of amplifier help in isolating DC without any additional circuitry. Active integrated antennas are widely used in communication systems to achieve

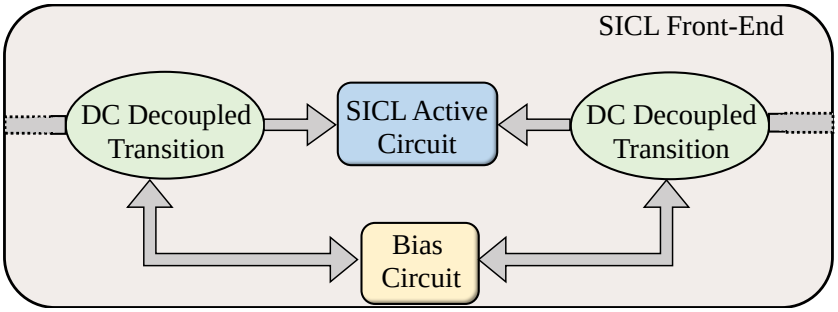

Figure 1.9 : System model depicting integration of active component in front end

switchable polarization and better bandwidth in a compact size. In [47], a T-shaped feed line electromagnetically coupled to a microstrip patch antenna exhibits inherent DC isolation between ports making it an attractive candidate for active integrated antenna application. To facilitate integration of active components, substrate integrated waveguide (SIW) is coupled to a corrugated substrate integrated waveguide [48] through an interdigital capacitor. An X-band amplifier [49] with calibration kit is proposed to measure the gain characteristics with respect to SIW ports. The size of this amplifier network is $1.5\lambda_g$. Semi-open structures like microstrip are prone to radiation loss at higher frequencies whereas shielded SIW occupies large lateral area. To overcome this problem substrate integrated coaxial line (SICL) is gaining popularity [51]. In SICL technology the inner conductor is not exposed for testing, hence a transition is required. Furthermore, DC block is necessary for isolation of DC bias circuitry in active and passive component integration. A possible configuration for this is in shown in Fig. 1.9. However, the challenging part is to implement a low-loss and wideband transition with DC blocking capabilities. Further, in literature so far the SICL based transitions and components are proposed using thin substrates ($\leq$0.5mm). Moreover, the popularly used SICL to grounded coplanar waveguide (GCPW) requires additional blind via and suffers from higher parasitics associated with increase in substrate height as well as fabrication complexity. On the other hand increased substrate thickness helps to improve antenna bandwidth and better field distribution.

1.3 BANDPASS FILTERS

1.3.1 Design of Bandpass filters

Bandpass filter is the foremost component in any RF front end architecture, used to select a region of electromagnetic spectrum [52]. With the rapidly evolving wireless services more than 50 filters are required in a modern day cellular phone is shown in Fig. 1.10. Bandpass filters are very prominent in design of RF-front end because:

1. **Noise Figure:** Being one of the first component of receiver the insertion loss dominates the overall noise figure.

2. **Linearity & Power requirement:** A well designed filter can bring down the power requirement of the RF chain, as now the down conversion doesn't have to be as linear as it would have been if dealing with a nearby interferer.

One of the major challenges in filter design is to attain good out of the band rejection with desired bandwidth in a compact size. The advancements and recent trends in design of modern filter for RF-front has been identified in Fig. 1.11. To achieve these goals bandpass filter have been designed in various technologies to enhance frequency selectivity as well as minimize the filter size.

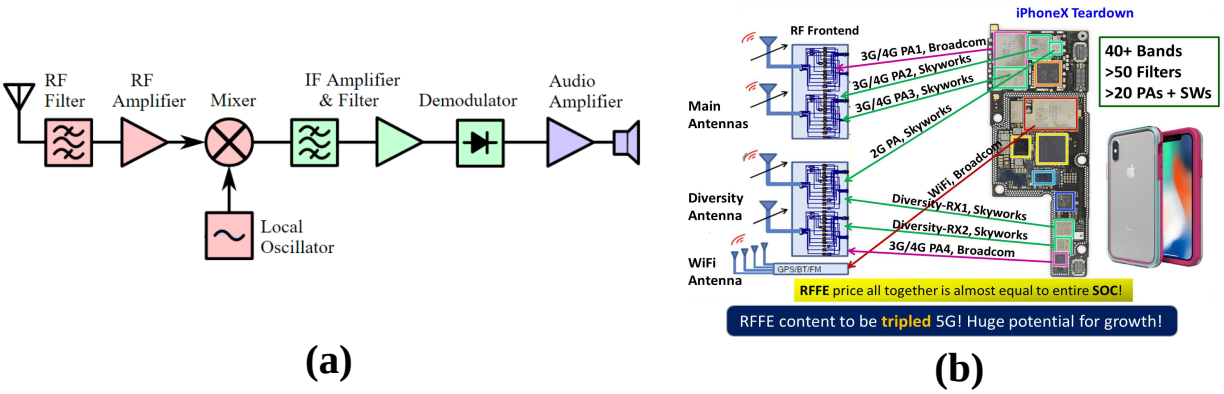

Figure 1.10 : Evolution of RF receiver architecture (a) Traditional RF receiver chain (b) Tear down of modern iPhone X (Courtesy: Prof. Dimitrios Peroulis, Purdue University (Purdue ECE695.3, RF Design: Passive & Active Components), Prof. Kenle Chen, University of Rhode Island)

Filters designed in microstrip technology are popular for their low profile and good integration capability. A notch perturbation in a microstrip ring resonator [53] is shown to excite degenerate modes for dual-mode response. In [54], radially oriented symmetric slotted arcs are etched in a circular patch to accomplish dual-mode as well as dual-band response. Though microstrip technology enjoys advantages like low profile and good integration ability, they are not preferable for operation in millimeter frequency range due to radiation loss and surface wave loss at high frequency. Traditionally, waveguide based bandpass filters were considered in millimeter-wave range. Substrate Integrated Waveguide (SIW) technology has been presented as an attractive alternative to the bulky waveguides in [23]. SIW supports high density integration in planar form with good power handling capability. Design of filters in SIW technology for millimeter-wave operation has been extensively studied. A dual-mode SIW hexagonal cavity has been realized [56] by means of side wall perturbation to achieve compact size with good out of the band response for X-Band. However, the SIW technology suffers from narrow mono-mode operation and large size which makes it not preferable for compact wideband application. In the recent time, SICL gained prominence as an attractive alternative to traditional coaxial line in plnar form [51]. . Design of a third-order bandpass filter in SICL technology using coaxial stubs [27] has been demonstrated for operation in X-band. Spiral resonators bounded by metallic vias [57]– [58] are utilized to design SICL bandpass filter with enhanced stop-band performance. Stepped impedance resonator implemented in SICL technology [12]-[14] have been shown to exhibit a wide stop-band response with narrow/wide-band performance. A $\lambda/2$ SICL cavity has been proposed in [62] for multi-band operation. However, due to large via to via distance, the fields weren't purely radially outward in this design. Rather, the field resembles more to stripline fields.

Design of bandpass filter poses several challenges for operation in millimeter-wave band such as featuring stable performance and combating radiation loss. A microstrip end-coupled bandpass filter operating at 29 GHz in [63] exhibits 2.3 dB insertion loss in the passband. In [64], an asymmetric high-Q dielectric resonator based filter has been realized for operation at 28 GHz. Though three-dimensional filters such as dielectric resonators offer low insertion loss they may not be favored due to increased complexity in integrating with other planar components. Utilization of high resistivity substrate with gold-plated microstrip line to mitigate radiation losses in bandpass filter at higher frequencies has been shown in [65]. Design of a 28 GHz 9th order interdigital low pass filter and 39 GHz 5th order bandpass filter on glass substrate using semi-additive pattering (SAP) [67] for 5G communication is demonstrated. A three pole substrate integrated waveguide

(SIW) [69] based bandpass filter using inductive via posts has been developed to operate at the 28 GHz band. Employing planar resonators within a SIW cavity realized in Low temperature co-fired ceramic (LTCC) technology [71] has shown enhancement in the operating bandwidth. In [72], air-filled SIW filter using inductive posts for low-noise applications is devised. Design of a high-Q H-shaped slot coplanar waveguide resonator [73] in a shielded box with coaxial transition is validated to operate at millimeter-wave band. A third order X-band filter [27] with short-circuited stubs conceived in SICL technology has been shown to have low footprint. SICL as a non resonating node has been introduced in a SIW bandpass filter [43] to increase the source to load coupling for achieving an additional transmission zero.

K_u-band has been a preferred choice to host satellite (very small aperture terminals) and RADAR communication [19]. Researchers have built and tested transceiver units [74] for mobile satellite reception in K_u-band as they are advantageous due to shorter wavelength (smaller size) and availability of wide bandwidth. Filters designed for this band require small footprint and lower insertion loss. In the past, novel bandpass filters in microstrip [21] and substrate integrated waveguide (SIW) technology [75, 76, 77] operating in K_u-band have been reported. . An SICL based third order bandpass filter [27] designed using short-ended stubs operating with center frequency at 10 GHz demonstrated an insertion loss of 0.35 dB. Recently, a fully shielded compact half-mode coaxial cavity filter [28] was proposed with multiple transmission zeros. SICL gained popularity among researchers as it shows lower insertion loss than the semi-open microstrip technology and smaller footprint compared to its SIW counterpart. An empty SICL (ESICL) filter designed in K_u-band by utilizing hollow substrate has shown to reduce dielectric loss [79]. So far in literature, the lateral metalized vias in SICL based circuits are only utilized to reduce crosstalk and form a shielded structure to minimize radiation loss.

1.3.2 Dual-band bandpass filters

Several aerospace and defense electronic systems use either a portion or all of the X, K_u and K frequency bands for satellite and RADAR communication[81]. The advent of high data-rate transmission pushed for duplex systems in modern hand-held equipment for simultaneous reception and transmission. In these microwave/millimeter systems, bandpass filter (BPF) serves as an integral element in the design of the RF front end. In [82], a dual-band traditional waveguide based BPF comprising of parallel connected cylindrical cavity with TE_{111} and TE_{112} modes [83]

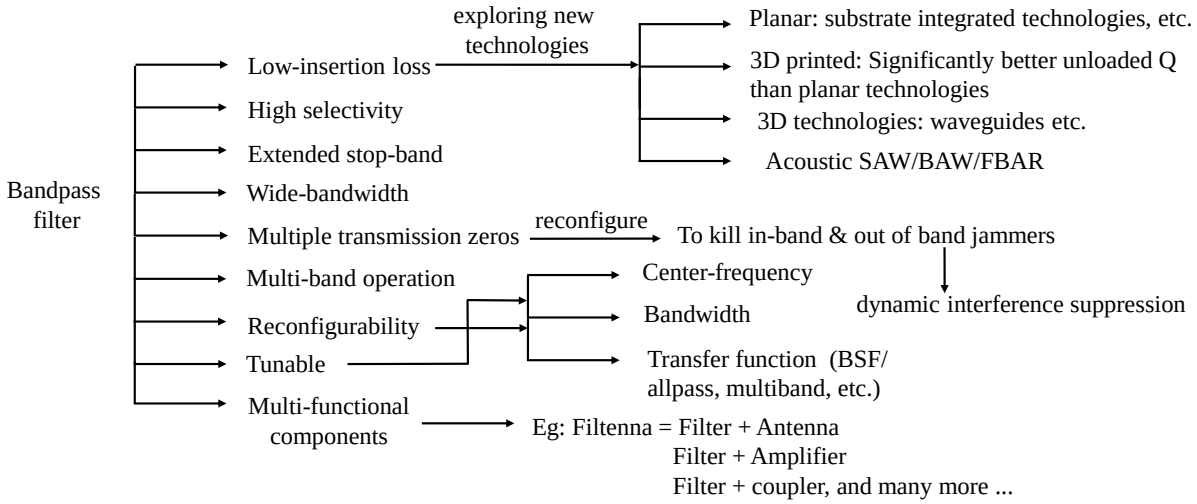

Figure 1.11 : Advancements and modern trends in filter design

for operation at 5 GHz and 7.5 GHz, respectively has been reported. On the other hand, easy to manufacture substrate integrated waveguide (SIW) has shown promising use in satellite ground terminal receiver [84]. The high-Q, shielded nature of SIW has been leveraged in [85] to design a third order dual-band filter using multiple inter-coupled rectangular cavities. To avoid interference between transmission and reception widely spaced dual-band SIW filter operating at 12 GHz and 17 GHz has been devised in [86] using multi-layer printed circuit board (PCB). But, SIW based circuits inherently occupy large lateral area [87]. Size of an SIW cavity can be reduced by bisecting along the fictitious magnetic wall iteratively to produce half-mode [88] and quarter-mode SIW cavity [89] at the cost of lower Q-factor. Moreover, other commonly practiced techniques such as etching slots on the ground plane of SIW cavity for size reduction and dual-band operation may cause radiation loss and affect the shielded nature of structure. With advancements in PCB fabrication, substrate integrated coaxial line (SICL) [51] technology has gained popularity for ease of integration [90], and low group delay over a wide bandwidth [91] due to its unimodal TEM based propagation. Contrary to the notion of metallic vias in SICL being only useful of lateral shielding, a novel perturbation technique has been demonstrated utilizing the metallic vias to design highly selective low loss K_u-band BPF [92]. Novel square-shaped SICL cavity was devised to design a [93] dual-mode BPF and later extended its use in a cavity backed slot antenna [94] & half-mode SICL filter. The wide-unimodal propagation in SICL structure holds the potential to develop dual-band filters with widely spaced bands at millimeter-wave frequency range.

1.3.3 Bandpass filters with enhanced selectivity and out of band rejection

Coexistence of multiple wireless standards in limited spectrum requires advanced filtering functions such as controllable bandwidth [95], dual-band [96], and wide out-of-band rejection [97]. The challenges in filter design grow manifold with increase in operating frequency. Though the widely used planar microstrip technology [21, 22] shows potential in development of filters in low cost and compact size, its utilization in higher frequency bands is limited due to poor shielding and radiation loss by its semi-open structure. Novel technologies such as low temperature co-fired ceramic (LTCC) [74] and low crystal polymer (LCP) [98] have been explored in the past for design of K_u-band multilayer bandpass filter. Substrate integrated waveguide (SIW) has emerged as one of the sought-after self-shielded planar guiding media with relatively less fabrication complexity to design microwave and millimeter-wave circuits [99, 100, 101, 102]. However, SIW occupies larger area than TEM based circuits and cannot offer broad-bandwidth due to inherent narrow mono-mode bandwidth. An interesting solution to this problem was provided by substrate integrated coaxial line (SICL) [51] technology having broad-bandwidth owing to the unimodal TEM based transmission in a compact form factor. An empty SICL (ESICL) filter operating in K_u-band by utilizing hollow substrate to reduce dielectric loss was reported in [79]. Design of bandpass filter with extended stop-band using half-wavelength stepped impedance resonator in SICL technology has been demonstrated in [103]. Recently, novel single-layer implementation of planar dual and triple-mode coaxial filters [107, 108, 109] with advanced filtering response has been explored.

The literature review reveals the need for exploring the new technologies to design bandpass filter with wide bandwidth, flexible transmission zeros and widely spaced dual-band operation with low-loss in self-shielded and self-packaged form factor.

1.4 BALUNS

1.4.1 Wide-band Baluns

K-band is the region of electromagnetic spectrum that holds great amount of prominence as it hosts operation of critical services such as satellite and RADAR communication. In this band high-data rate with good resolution for RADAR communication can be achieved. It is important

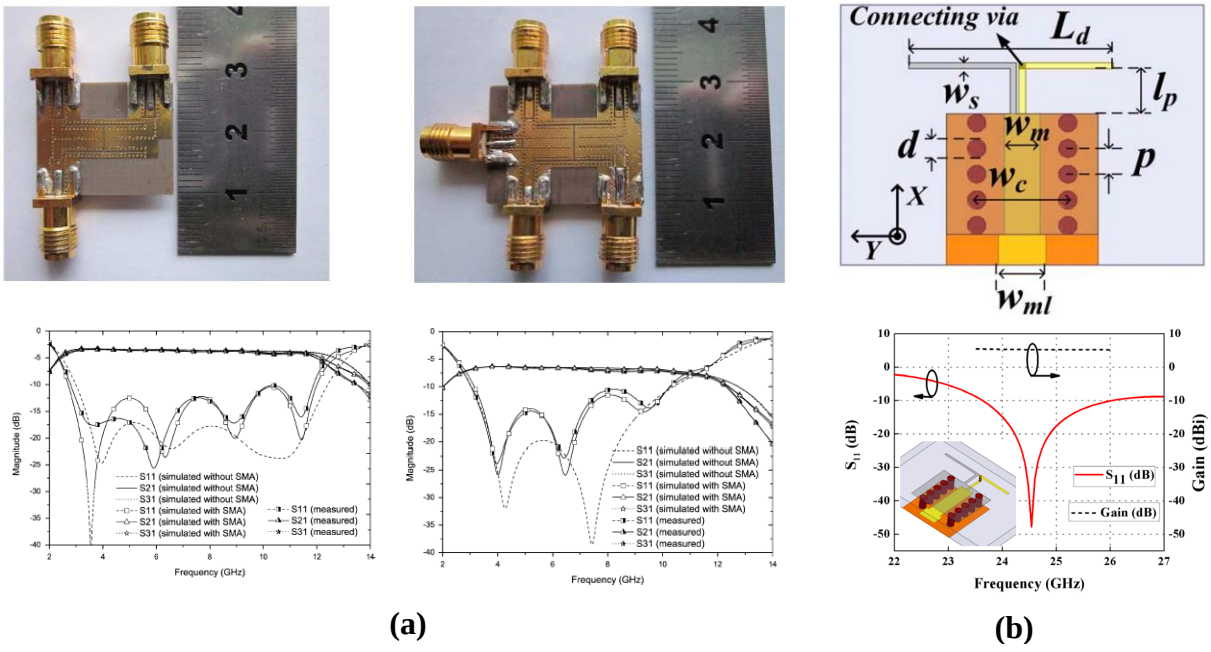

Figure 1.12 : Design development of baluns in SICL technology (a) An ultra-wideband single and dual balun (Courtesy:F. Zhu, W. Hong, J. -X. Chen and K. Wu, "Ultra-Wideband Single and Dual Baluns Based on Substrate Integrated Coaxial Line Technology," in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 10, pp. 3062-3070, Oct. 2012) [7]. (b) Utilizing the SICL line as a balun to feed a dipole antenna (Courtesy: S. Mukherjee, "Design of Substrate Integrated Coaxial Line (SICL) fed dipole antenna for K band application," 2017 IEEE Applied Electromagnetics Conference (AEMC), 2017, pp. 1-2 [8].

that the technology used to design components for operation in this band are low-profile and compact in size to save crucial on-board space. In millimeter-wave communication systems, baluns are extensively used as feeding network for dipole antennas, and in design of active circuits such as mixers, push-pull amplifiers, frequency multipliers and oscillators [110]. The use of composite right and left-handed materials at the output of a Wilkinson power divider in microstrip technology to realize balun has been shown in [111]. A microstrip to stripline transitioning Y-type balun has been explored in [112] to feed a complementary spiral antenna. In [113], two planar marchand baluns realised in microstrip and CPW configuration have been presented to operate in millimeter-wave frequency range. Though several circuits have been realized in these popular technologies, the problem of high radiation loss and surface wave loss is a serious concern in microstrip technology at millimeter-wave range. The stripline based balun ceases to provide the necessary lateral shielding for densely packed circuits operating at millimeter-wave frequency range. An active CMOS balun operating at 24 GHz for K-band application has been demonstrated in [115]. Design of baluns for 5G communication employing microstrip to slotline transition [116] has been utilized for ultra-wideband operation. Substrate integrated waveguide (SIW) technology has been significant in designing millimeter-wave range components due to its implementation in planar form. A broadband balun realized using equal-spilt power divider and an out of the phase signal has been shown [117] in SIW technology to operate in K-Band. In [118], design of a mixer employing a SIW based balun operating in 40 GHz to 50 GHz range is realized. A highly selective wide-band balun with filtering response is conceived in [119].
The working of UWB-Marchand Balun developed in SICL technology has been verified in [7] as

shown in Fig. 1.12(a) & (b). Out of phase signals propagating in the top and middle layer of SICL is used in [8] to excite a dipole antenna operating at 24.5 GHz as depicted in Fig. 1.12(c). Even with the extensive research presented above, development of wideband baluns in a compact form factor at millimeter-wave frequency band is much required.

1.4.2 Dual-band Baluns

The issue that has been challenging the world of wireless communication industry in the recent time is the proliferation of cellular network users. Utilizing multiple bands of the spectrum and shifting to less crowded millimeter-wave range has been an effective way to address this issue so far. It is predicted in near future the cellular communication industry is to be adopting 5G standards. European Union (EU) and USA will be utilizing the unlicensed shared spectrum of 5.9 GHz to 6.4 GHz for 5G communication (Sub-6 GHz Band) [120] and in the higher frequency range, 28 GHz is proclaimed to be used all over the world. To accommodate such demanding requirement of dual-band operation, a new class of components will be need of the day soon [121]. Balun serves as a vital component in almost all millimeter-wave communication systems. The need for transformation of an unbalanced signal to balanced form has applications in excitation of dipole antennas, design of active circuits such as mixers, push-pull amplifiers and frequency multipliers. A 20/44 GHz dual-band branch-line balun realized in microstrip technology exhibited amplitude imbalance of 3 ± 3.5 dB at the output ports [122]. In [118], a millimeter-wave third harmonic mixer comprising of SIW balun is conceived. SICL facilitates single-mode TEM propagation of wave over a wide frequency band provides the opportunity to realize dual-band baluns with large frequency ratio. However, further investigations are required to use SICL for developing compact baluns that can operate at the sub-6 GHz band as well as 28 GHz millimeter-wave band of the upcoming 5G communication.

1.5 THREE AND FOUR PORT NETWORKS

Quadrature hybrid/ branch line coupler (BLC) serves multiple purposes in a modern communication system. It is used as a quadrature splitter in IQ modulator, employed in butler matrix for steering the beam of antenna arrays and in double balanced mixer diode to suppress local oscillator (LO) signal at RF port. [125]. Conventional quadrature hybrids suffer from large surface area and generate harmonics at odd multiples of fundamental frequency as they are built using $\lambda_g/4$ transmission lines. Substrate integrated waveguide (SIW) gained popularity as a planar alternative to traditional waveguide for implementation of microwave components at higher frequencies. In [126], an equal split compact directional coupler based on conductor backed slotline and half-mode SIW was conceived. To further reduce the size, slotted 3-dB coupler in half-mode folded SIW [127] has been proposed for operation in X-band. In SIW based circuits, the higher order modes are more closer to the fundamental frequency when compared to other technologies such as microstrip, thereby offering poor out-of the band response. In addition, the size reduction achieved in SIW using half-mode technique compromises on shielding. A BLC has been reported in SICL technology [9] utilizing $\lambda_g/4$ transmission lines. Directional coupler with single and dual-band operation for 20 dB coupling level has been explored in [11]. In [128], design of wide-band SICL based octave directional couplers was experimentally verified. A dual-band antenna fed by a dual-band coupler [10] was realized using short-ended coaxial stubs in SICL technology. Further, utilization of opened-ended stubs to realize dual-band circuits in SICL has been explored in [129] for 5G communication. Another coupler that is widely used in communication systems is rat-race coupler. Rat-race coupler forms an integral component in design of widely used push-pull amplifiers, singly balanced mixer, and beamforming network for low-cost smart transceiver systems[130]. Traditionally built using quarter-wave transformers in TEM based circuits, this four port coupler provides sum and difference signal at the output

depending on the excitation of input ports. With extensive research over years this widely used 4-port passive component has evolved to have several new functionalities such as tunable power division [131], common-mode noise suppression [132], wide-bandwidth [114], reconfigurability in terms of frequency [133] and bandwidth [134]. The couplers proposed in [131, 132, 114, 133, 134] work at one single-band of frequency spectrum. But with rapidly evolving needs of current generation utilization of multi-frequency spectrum is desirable[136, 137, 140, 135]. Dual-band rat-race couplers utilizing open/short stubs suffer from narrow bandwidth [135]. A technique to improve the fractional bandwidth (FBW) of a dual-band coupler up to 4% has been shown in [136]. Rat-race couplers have been extensively researched in several technologies such as microstrip [137], substrate integrated waveguide [138, 139], LTCC [140], glass integrated passive devices [141]. A ring-based rat-race coupler implemented in SICL technology was experimentally verified for 2 GHz. Geometrical layouts of previously implemented couplers in SICL technology has been illustrated in Fig. 1.13.

Also three port network such as power dividers is widely used in microwave/ millimeter-wave systems for design of a variety of applications such as in balanced amplifiers, inphase-quadrature (IQ) modulators, and antenna arrays. An SICL based 1 to 4 way power divider has been explored in [13] has been demonstrated for K-band as shown in Fig. 1.14.

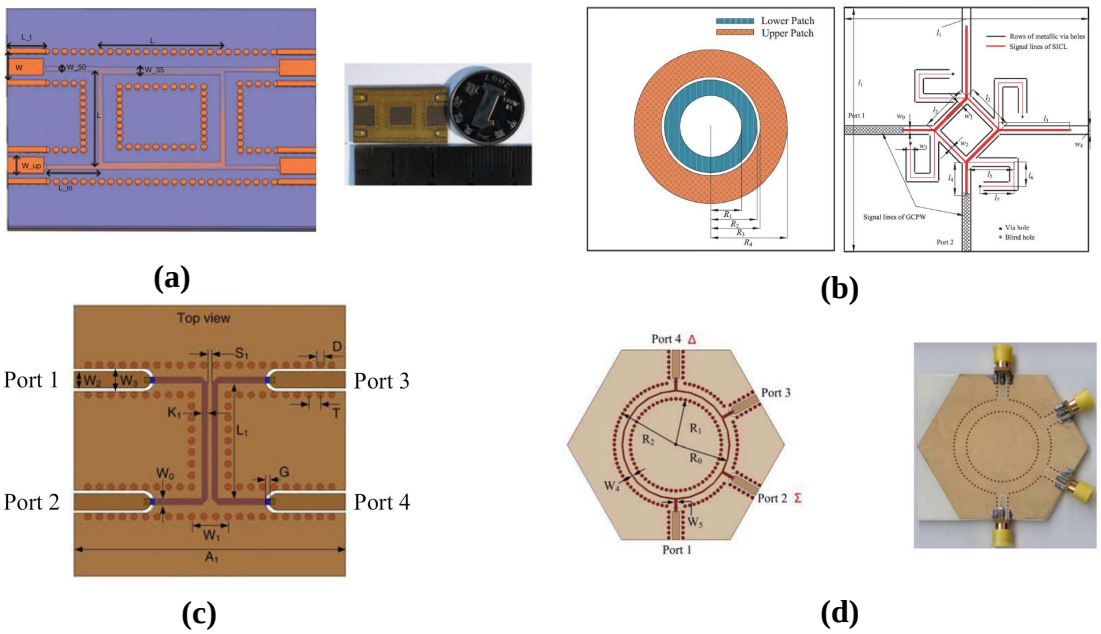

Figure 1.13 : Couplers implemented in SICL technology (a) A traditional 3 dB quadrature hybrid (Courtesy: W. Liang an et.al, Substrate integrated coaxial line 3 dB coupler," Electronics Letters, vol. 48, no. 1, pp. 35-36, January 2012) [9] (b) Application of SICL based branch-line coupler to excite dual-band antennas with circular polarization (Courtesy: Q. Wu, H. Wang, C. Yu, X. Zhang and W. Hong, "L/S-Band Dual-Circularly Polarized Antenna Fed by 3-dB Coupler," in IEEE Antennas and Wireless Propagation Letters, vol. 14, pp. 426-429, 2015) [10] (c) Loosely coupled SICL based directional coupler (Courtesy: S. Jun Yu, and et.al, "High directivity single and dual band directional couplers based on substrate integrated coaxial line technology," in 2013 IEEE MTT-S International Microwave Symposium Digest (MTT), June 2013, pp. 14) [11] (d) A ring-based rat-race coupler implemented in SICL technology (Courtesy: Q. Liu, et.al, "Broadband substrate integrated coaxial line to CBCPW transition for rat-race couplers and dual-band couplers design," Progress In Electromagnetics Research C, Vol. 35, 147-159, 2013) [12]

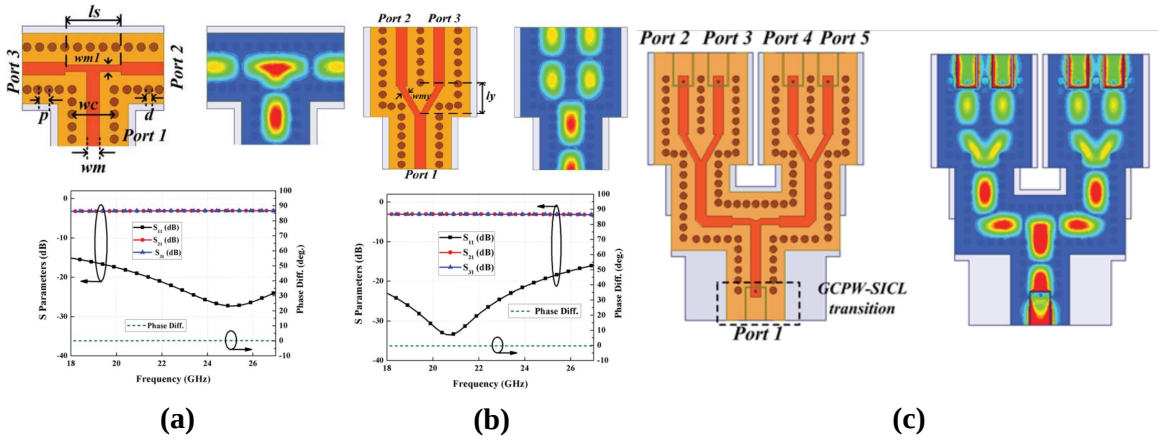

Figure 1.14 : One to four way SICL based power divider for K-band using T-type and Y-type power dividers (Courtesy: S. Mukherjee, "Design of Four-Way Substrate Integrated Coaxial Line (SICL) Power Divider for K Band Applications," 2017 IEEE MTT-S International Microwave and RF Conference (IMaRC), 2017, pp. 1-4]) [13].

1.6 FOUR PORT CROSSOVER

Crossover is commonly used in microwave/millimeter-wave systems to maintain electrical isolation between two physically overlapping transmission lines. It finds application in design of butler matrix for smart antenna systems and to maintain signal integrity in MMIC modules [142, 143, 144]. Various design techniques have been explored to improve the bandwidth of microwave crossover. These techniques can be broadly classified as i) Cascading/ cascoding branch-line structures [145, 146], ii) utilizing microstrip to coplanar waveguide (CPW)/ slotline transition [148, 149, 150, 151, 152] iii) Microstrip resonator [153, 154, 155, 156] iv) Multilayer [162, 163, 164, 165, 166] structures. In [145], a crossover designed by cascading four sections of branch line coupler exhibits a fractional bandwidth (FBW) of 33% with a peak group delay of 13 ns and 1 ns variation over the entire bandwidth. Although this technique is demonstrated up to cascading of 7 sections to further improve the bandwidth, it occupies large area and has poor group delay characteristics. To avoid large size caused by cascading, two branch line structures are cascoded [146] to exhibit 55% FBW. A class of crossovers employing microstrip based transitions have been investigated for ultra-wide bandwidth (UWB). In [148], a microstrip to conductor backed CPW transition is used to route the signal through bottom plane to preserve isolation between the microstrip line in top plane. The proposed crossover presents a wide bandwidth ranging from 0.1 GHz to 6 GHz in a very compact size. A via-less ultra-wideband microstrip to slotline transition is devised in [149] to obtain high isolation between intersecting channels with 0.1 ns deviation in group delay between 3.1 to 10.6 GHz. Subsequently in [150, 151, 152] crossover design using microstrip to CPW based transition for UWB application has been explored. Slots etched in overlapping portion of the transmission line [150, 152] to improve isolation degrades the necessary equiphase relationship between both the paths. Additional delay lines [150] and slots [152] utilized to externally compensate the phase difference increase design complexity and lateral area. Microstrip patch resonator based crossovers have been a popular choice for their better power handling capability in RF systems. A nested ring resonator connected to circular patch [153] provides wide FBW of 44% due to its multi-mode characteristics. Further, low deviation in group delay of 0.25 ns is observed over the entire bandwidth. To attain compact size, several variations of microstrip resonators based crossover such as square patch [154], circular slotted patch [155] and higher orders of sierpinski carpet [156] based microstrip patch have been experimentally validated. A low deviation in group delay is observed in their operating band due to the inherently

narrow bandwidth of the microstrip resonator. A wideband substrate integrated waveguide (SIW) crossover is utilized in a 4×4 broadband butler matrix [157]. Design of multilayer crossover provides better design flexibility at the cost of increased fabrication complexity. In [162], a novel multilayer crossover employing electric and magnetic coupling to achieve good isolation at millimeter-wave band has been demonstrated in SIW technology. Narrow monomode bandwidth of SIW structure makes it unsuitable for design of compact wideband crossovers covering lower frequency bands like L, S, C and higher bands like X and Ku simultaneously. Crossovers derived from slot coupled directional couplers [165, 164] have been explored for design of butler matrix. An UWB multilayer crossover is proposed utilizing microstrip line in one channel and slot coupled transitions in other to maintain isolation between both the channels.
SICL technology due to its non-dispersive nature as a transmission line is an excellent choice to implement wide band crossover in a planar form-factor. However, further investigations are required to achieve low path difference, low group delay in a compact size.

1.7 FILTERING ANTENNA

Steadily growing modern communication requires transition to multi-functional components for enhanced operation of RF-front end [130]. The multi-functionality is brought into a single component by integrating two or more components to save crucial on-board space and improve the overall performance. A three-port network doubling as microstrip based bandpass filter (BPF) and antenna depending on excitation of relevant port has been reported in [167]. To achieve lower insertion loss in BPF and mitigate feed network loss in antennas, substrate integrated waveguide filtenna was proposed in [168]. SIW based filter-antenna with on-board sensor [169] extended the idea co-design for microwave sensing applications. Transitioning to a technology that realizes a coaxial line integrated in substrate [51] enables design of microwave based components with better bandwidth in compact size.
The low-loss SICL is a worthy candidate to explore a co-design approach for developing filter-antenna for widespread utilization in compact hand-held devices.

1.8 ORGANIZATION OF THESIS

The thesis is organized into six chapters with **Chapter-1** as an introduction to a new technology namely substrate integrated coaxial line and its need in the current generation wireless systems is discussed. The basic working mechanism of this transmission line and its application are reviewed. A variety of components used in the modern RF-front end such as transitions, bandpass filters, baluns, quadrature hybrid, 180° couplers, crossover, and antennas are studied in detail. Furthermore, state of the art literature is surveyed the context of microwave/millimeter-wave circuits for enhanced functionality.

Chapter-2, starts with detailed discussion on design of SICL transmission line and derives the closed form equation of the characteristic impedance of SICL line as a function of its physical and electrical parameters . The study describes the identification of the optimal width of outer conductor to thickness of substrate (W_{out}/H_{sub}) ratio to utilize the coaxial nature of SICL. Robustness of the proposed formula is affirmed by testing the fabricated SICL line with different dielectric constant and thickness. SICL presents itself in a packaged form, hence an efficient transition is required for testing and integration with other planar transmission line. A wideband coaxial to substrate integrated coaxial line (SICL) transition implemented as a male to female connection seen in coaxial connections is proposed. A novel topology to facilitate a transition from microstrip line to SICL without the need for any blind is analyzed and experimentally verified up to 40 GHz. A new SICL based wideband transition to isolate DC bias circuitry required for active circuit integration in system design is proposed for X-band.

Chapter-3 explores design of SICL based bandpass filters in compact size with wide-bandwidth, high selectivity, dual-band operation and with enhanced flexibility in adjusting the filtering response. A novel dual-mode SICL based bandpass filter operating at 28 GHz, targeted for 5G application is conceived by exciting the degenerate modes in the middle layer square patch by etching cross-shaped slots. In order to further reduce the size of the cavity, a half-mode cavity is proposed by bisecting along the fictitious magnetic wall of the SICL cavity. A bandpass filter devised by coupling a pair of half-mode and quarter-mode cavities demonstrated single and dual-band functionality with flexible frequency response. Later, a contrary to the notion of metallic vias in SICL being only useful of lateral shielding, a novel perturbation technique has been demonstrated utilizing the metallic vias to design highly selective low loss Ku-band BPF. Further, a new class of planar coaxial filters with enhanced bandwidth and transmission zeros exhibiting high degree flexibility to improve selectivity as well as out of band rejection is demonstrated. all the experimental prototypes are fabricated and tested using vector network analyzer to affirm their functionality.

Chapter-4 is dedicated to design of three-port and four port networks that are widely used in RF-front end architecture. SICL based baluns for wide-bandwidth and dual-band operations are proposed. The performance of the dual-band SICL line is analyzed and range of realizable frequency ratios is determined from the analytically derived equations. Quadrature hybrids built using quarter-wavelength lines suffer from odd harmonics. A compact SICL based quadrature hybrid operating at 10 GHz with controllable harmonic rejection is realized using shielded open-ended coaxial stubs. In order to further enhance the bandwidth and spectrum utilization a dual-broadband Rat-race coupler operating simultaneously at X-Band and K-band with harmonic suppression up to 40 GHz is realized in SICL technology. Later, SICL-based wideband crossover with low phase difference and group delay is conceived for 0.2 GHz to 20 GHz band. Finally the design and fabrication of wideband branch-line coupler two-stage Wilkinson power divider covering the entire *Ku*-band is discussed in detail.

Chapter-5 deals with design of multi-functional and integration of SICL based components. Firstly, a SICL filter-antenna operating at 25.45 GHz is developed by integrating a slot antenna with 5^{th} order parallel coupled $\lambda/2$ SICL resonators. Systematic integration of diplexer and high gain antenna has been practically demonstrated. Finally, a wideband six-port covering complete K_u-band has been realized in SICL technology.

Finally **Chapter-6** concludes the thesis and also discusses future scope of the thesis.

…