

Implementation of Substrate Integrated Coaxial Line based Antenna Array

4.1 Introduction

The path loss at 5G mm-wave frequencies are high as compared to microwave frequencies, due to shorter wavelength as evident from Friss transmission line equation. The challenge exists for designing the RF front end, especially antennas at millimeter wave frequencies with high gain. The applications in millimeter wave frequencies require the high gain, compact antenna design for its use in modern wireless communication applications. High gain systems is generally achieved by implementing array antennas. In this chapter, novel crossed dipole antennas and half mode SICL cavity-based antenna arrays are proposed that exhibit wide band performance to meet the requirements of 5G communication. Further, reconfigurability in polarization, direction, etc. has been achieved in the antenna using mm-wave switches. These antennas and arrays are designed to cover the 3GPP n257, n258 and n261 FR2 bands that make them suitable for practical 5G deployment. Beam steering antennas are another possible solution to support wide coverage. SICL is expected to become a popular attractive candidate for designing antenna arrays especially where small form factor is preferred as in modern hand-held devices and customer premises equipments (CPE).

This chapter deals with designing of high-gain antenna arrays for 5G mm wave applications. The chapter ⁴ is organized as follows. It begins with designing slot antenna arrays in Section 4.2. Firstly, in Section 4.2.1, 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 in Section 4.2.2 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 in Section 4.3. Section 4.4 deals with a SPDT RF switch based novel SICL switching board, which is utilised for dual polarized antenna in 4.4.2 and simultaneous dual beam pattern reconfigurable antenna application in 4.4.3 over wide n257 band. Further, Section 4.5 deals with stacked configuration of the HMSICL antenna to improve the bandwidth of the proposed HMSICL array.

⁴This chapter is based on the publication [Baghel and Mukherjee, 2018a, 2019, 2022c].

4.2 Design of Substrate Integrated Coaxial Line based Slot Antenna Arrays

According to 5G communication standards for millimetre wave frequencies (above 24 GHz) countries like USA, China, Australia and European Union (EU) have allocated licensed band centred at 25 GHz (24.5 GHz to 27.75 GHz) [Qualcomm, 2017]. Antenna arrays are an imperative requirement for high gain antennas in modern communication. Arrays are useful particularly in long range communication to design high gain antenna. Slot antenna is advantageous for its easy implementation, light weight design, inexpensive, mass production and effortless incorporation in active integrated circuits. A series-fed slot element transversely coupled to a microstrip line has been designed using the transmission line theory in [Tulintseff, 1993]. Bandwidth enhancement of microstrip line based slot antenna has been shown in [Okura and Arai, 2015] by placing slots along both the edges of the microstrip line. Slot-coupled feeding technique for two-dimensional antenna arrays has been demonstrated to have better radiation pattern of linear antenna arrays in [Wincza and Gruszczynski, 2011]. In this Section, Substrate Integrated Coaxial Line (SICL) has been used to design a slot antenna array for millimetre wave applications. The inherent out of phase current distribution in the middle strip with respect to the top and bottom conducting plates of the SICL transmission line provides versatility for radiation in both side of the antenna. Thus, dual beam is comfortably obtained by making perturbations in the top and bottom plates of the SICL transmission line. The designing of the array starts with firstly designing a single C-shaped slot element on the top plate of the SICL transmission line that provides broadside radiation. Next, a double C-shaped slot radiator comprising of a slot on the top and a slot on the bottom plate of SICL has been studied for radiations in both sides of the antenna.

4.2.1 Design of a Substrate Integrated Coaxial Line based 2 x 4 Slot Antenna Array

In this Section, SICL based 2 x 4 C-shaped Slot Antenna Array fed by Substrate Integrated Coaxial Line (SICL) working in the millimeter wave frequency band is presented. As a starting point for the design, a 1 x 2 C-shaped Slot antenna array is designed to be operated at 29.35 GHz with a gain of 6.6 dBi. The proposed 2 x 4 C-shaped Slot Antenna Array exhibits high gain of

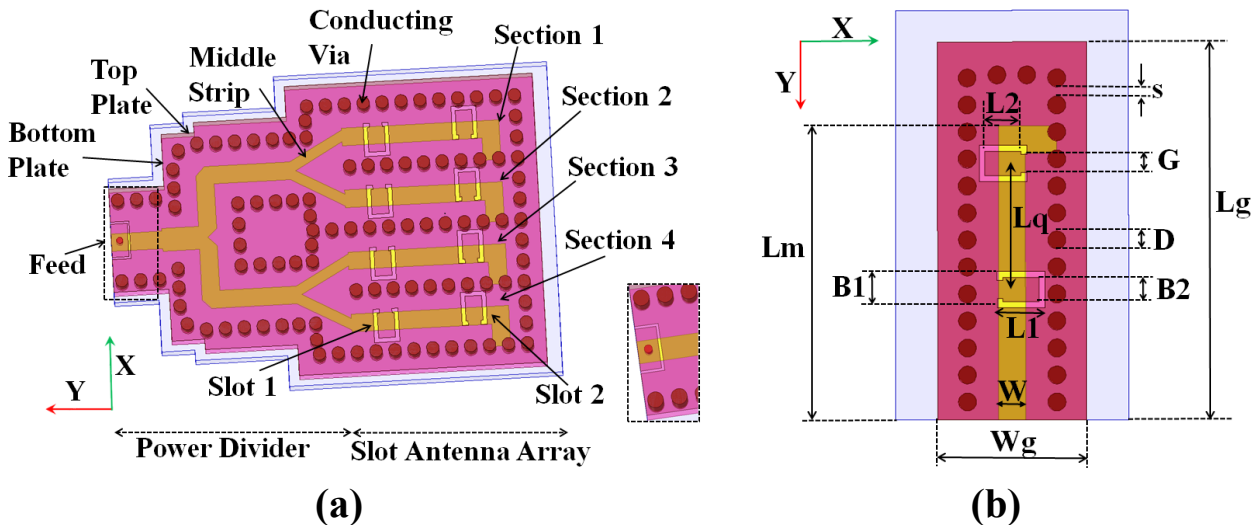


Figure 4.1: (a) The proposed 2x4 C-shaped slot antenna array with SICL feed section along with inset-feed point and (b) Top View of 1x2 C-shaped slot antenna array and its dimensions.

Dimensions (in mm): $L_g = 12.6$, $W_g = 5$, $L_m = 9.8$, $W = 0.9$, $L_1 = 1.6$, $L_2 = 1.2$, $B_1 = 1.2$, $B_2 = 0.8$, $L_q = 4.2$, $G = 0.6$, $s = 0.3$, $D = 0.6$

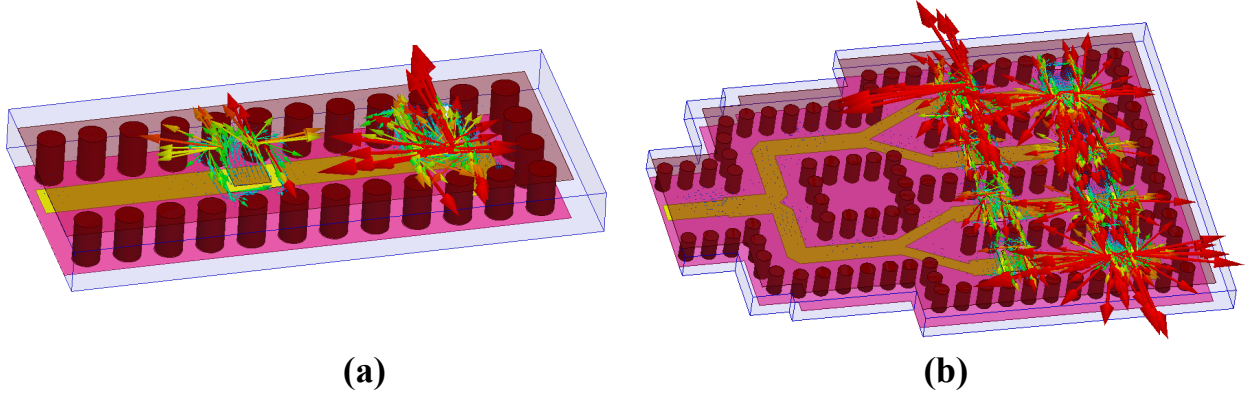


Figure 4.2: Vector Surface Current distribution on the top plate containing the slot in (a) 1 x 2 and (b) 2 x 4 C-shaped slot antenna array.

10.6 dBi at 29 GHz. The 4 sections of the slot antennas array is fed with in-phase field using a SICL power divider. This makes the complete design compact and low profile. The via section encapsulating the middle conductor strip of the SICL section provides good shielding of the feeding network. The designed antenna array has front to back ratio of 17.4 dB. The antenna is useful in LMDS band and possible 5G applications.

4.2.1.1 Working Principle

In this Section, first the design of one-dimensional 1 x 2 C-shaped slot antenna array is presented followed by two-dimensional 2 x 4 C-shaped slot antenna array. The antenna has been designed using two layers of Taconic TLY-5A dielectric substrate of size 15 mm x 21 mm (thickness of 0.5 mm, $\epsilon_r = 2.2$). The individual 1 x 2 C-shaped slot antenna array is fed with SICL based four way power divider [Mukherjee, 2017a]. The design of 1x2 C-shaped slot antenna and the dimensions are shown in Fig. 4.1. The middle strip is shorted to the ground by the conducting via. The first slot is placed at quarter-wavelength ($\lambda/4$) distance from the short circuited end, which effectively acts as the open-circuited line for the first slot. The second slot is kept at a spacing (Lq) of $\lambda/2$ from the first slot. The width of the middle strip (W) is adjusted to achieve 50Ω characteristic impedance keeping the height of the substrate constant [Gatti *et al.*, 2006]. The opening (G) of the slot changes the resonant frequency and hence it has been optimized to resonate the 1 x 2 slot design in LMDS band at 29.35 GHz with -10.9 dB return loss. The width of the slot is 0.2 mm and the mean length of C-shaped slot is 4 mm [Wong *et al.*, 2002].

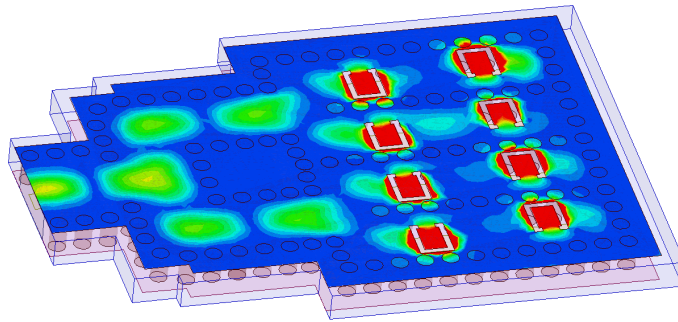


Figure 4.3: Electric Field (magnitude) distribution of the top plate containing the slot in 2x4 C-shaped slot antenna array.

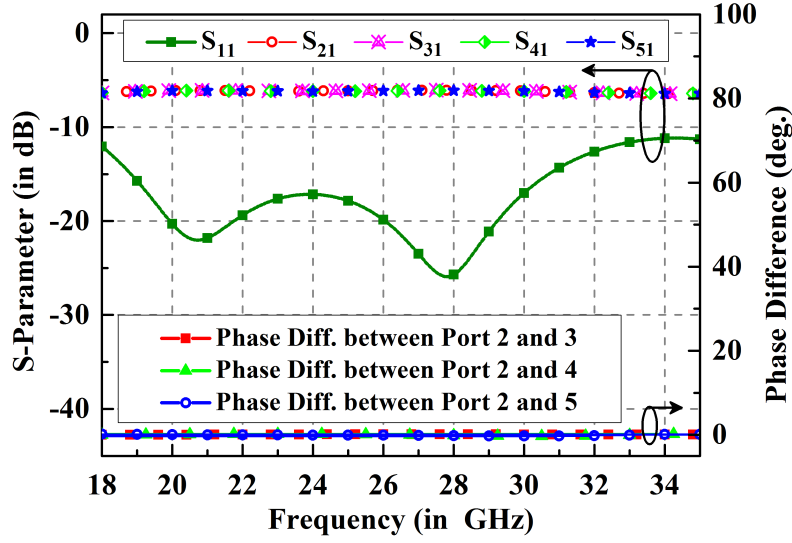


Figure 4.4: Performance of SICL one to four power divider.

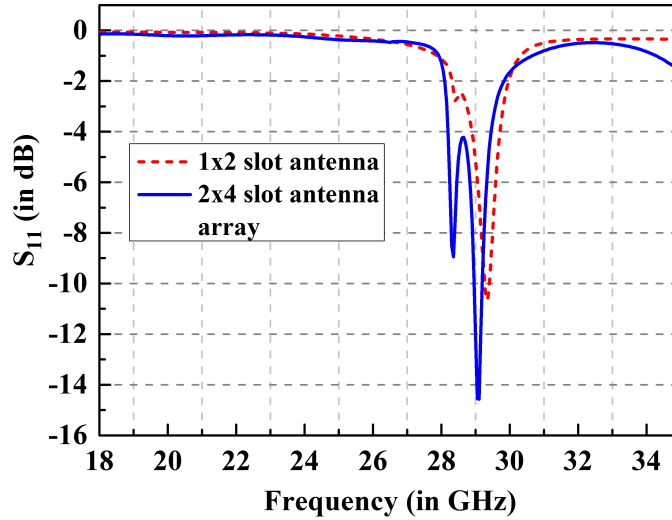


Figure 4.5: Reflection Coefficient of 1x2 and 2x4 C-shaped slot antenna array.

The design of the 2 x 4 slot antenna array is shown in Fig. 4.1(a). The slots are shifted from center to adjust coupling of slot with the SICL feeding line to ensure equal excitation to each slot. To compensate 180° phase shift of successive slot antenna element, the orientation of the slots are changed. As depicted in the Fig. 4.2, there is 180° out of phase surface current in the slots. The vector surface current exciting the slot in 1 x 2 and 2 x 4 slot antenna array is shown in Fig. 4.2. The 1 x 2 slot array section are placed side-by-side and as a result the element spacing between successive section becomes less than $\lambda/2$. This makes the total size of the antenna array much smaller than that of SIW and waveguide antenna array. However, high mutual coupling is present and a shift in corresponding resonance is observed. To mitigate this, the slot element is tuned to resonate at same frequency. The resultant electric field as shown in Fig. 4.3, is radiated in same phase and interfere constructively to achieve a high gain at broadside direction. Four sections of 1 x 2 slot antenna is fed by the SICL transmission line using one to four SICL based power divider

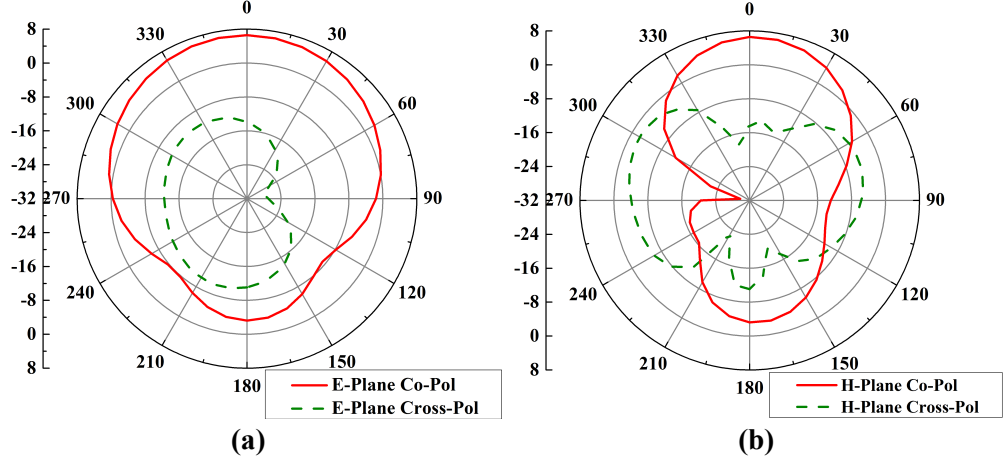


Figure 4.6: (a) E-plane at $\phi = 0^\circ$ and (b) H-plane at $\theta = 90^\circ$ radiation pattern for 1 x 2 C-shaped slot antenna array.

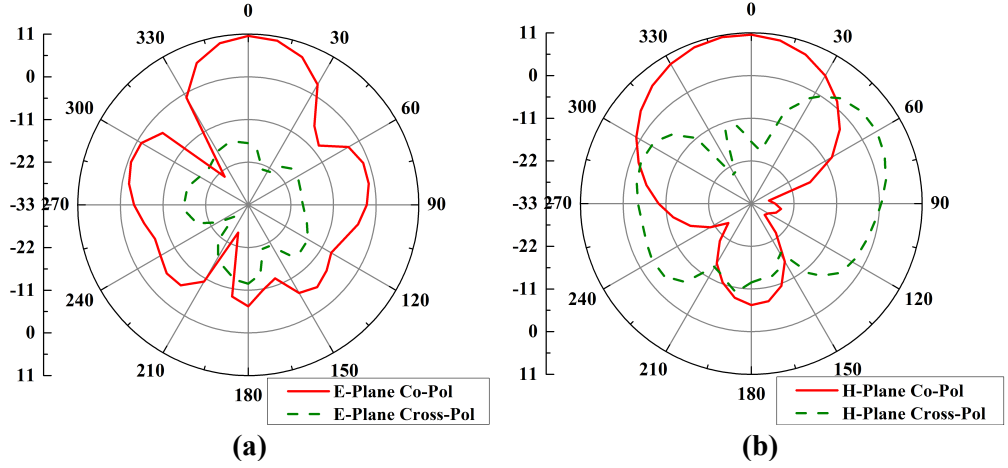


Figure 4.7: (a) E-plane at $\phi = 0^\circ$ and (b) H-plane at $\theta = 90^\circ$ radiation pattern for 2 x 4 C-shaped slot antenna array.

[Mukherjee, 2017a].

4.2.1.2 Results

With the simplified SICL feed in the proposed antenna array, the feeding network has been completely shielded and we are able to achieve a compact design. The performance of the power divider is shown in Fig. 4.4. The power divider provides equal power to all the output ports with the level -6 ± 0.2 dB with the phase difference between the output ports below 0.25° . The reflection coefficient is -20 dB at the operating frequency.

The HFSS simulated reflection coefficient of the one-dimensional 1 x 2 slot and two-dimensional 2 x 4 slot antenna array is shown in Fig. 4.5. Resonance for both the slot antenna arrays occur at 29 GHz. The fractional impedance bandwidth of 0.8% (238 MHz) is obtained for the two-dimensional 2 x 4 C-shaped slot antenna array. The gain obtained with a 1 x 2 slot antenna array is 6.6 dBi and that with 2 x 4 slot antenna array is 10.6 dBi at the operating frequency. The radiated pattern of the slot antenna is shown in Fig. 4.6 and 4.7.

For the two-dimensional 2 x 4 C-shaped slot antenna array a side-lobe level of -11.4 dB is observed due to equal excitation of array elements. The front to back ratio (FTBR) of the one-dimensional 1 x 2 slot array antenna is 9.76 dB. The cross-pol component is 20.4 dB below the co-pol component in both the E-plane and H-plane radiation pattern for 1 x 2 slot antenna array as shown in Fig. 4.6. Similarly, for the 2x4 slot antenna array cross-pol component is 27.6 dB below the co-pol component in E-plane and H-plane. Also, the front-to-back ratio (FTBR) of the two-dimensional 2 x 4 slot array antenna as observed is 17.4 dB as shown in Fig. 4.7.

The study of the presented 2 x 4 slot antenna array exhibits unidirectional radiation. In the next Section, the design of slot antenna array for bidirectional radiation is presented.

4.2.2 Design of a Substrate Integrated Coaxial Line based Dual Beam 6 x 4 Double Slot Antenna Array

A compact and low-profile dual beam slot antenna array operating at millimetre wave frequency is presented in this Section. A 6 x 4 C-shaped slot antenna array has been designed using Substrate Integrated Coaxial Line (SICL) technology. The feeding section of the array is SICL based one to four way power divider that feeds the four 6 x 1 antenna sub-array. The placement of the slot disturbs the surface current in the outer conductor which excites it to radiate in free space. The width of the SICL is much less than $\lambda_g/2$, this makes SICL compact as compared to other feeding networks, low profile and suitable for broadside applications. The proposed 6 x 4 C-shaped slot antenna array operates at 25.16 GHz with 3 dB beamwidth of 46° and provides a gain of 9.87 dBi. This antenna is particularly suitable for cost effective solution for multi user communication at millimetre wave frequency.

4.2.2.1 Working Principle

SICL transmission line consists of a middle conducting strip between two dielectric substrates (Taconic TLY-5A, permittivity $\epsilon_r = 2.2$, height 0.5 mm each). The width of the middle strip is chosen for 50 Ω characteristic impedance, keeping the height of the substrate constant [Gatti *et al.*, 2006]. The proposed SICL based 6 x 4 slot antenna array for dual beam is shown in Fig. 4.8(a). A single C-shaped slot on the top plate of the SICL transmission line is kept at quarter

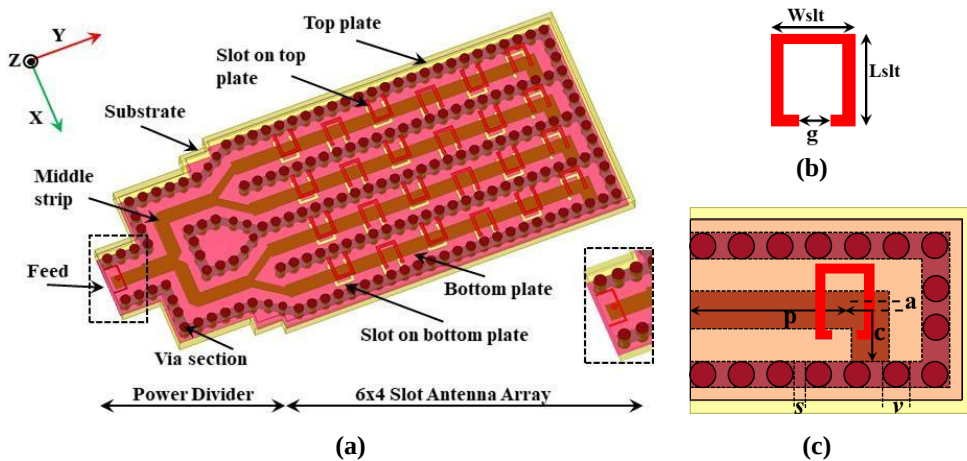


Figure 4.8: (a) Isometric view of the proposed 6x4 C-shaped slot array antenna; inset feed point GCPW to SICL transition. Geometry of the fundamental unit of the array. (b) C-shaped slot, and (c) top view of double slot element radiator ($g = 0.6$ mm, $W_{slt} = 1.35$ mm, $L_{slt} = 1.75$ mm, $a = 0.3$ mm, $c = 1.8$ mm, $p = 3.6$ mm, $s = 0.3$ mm, $v = 0.6$ mm).

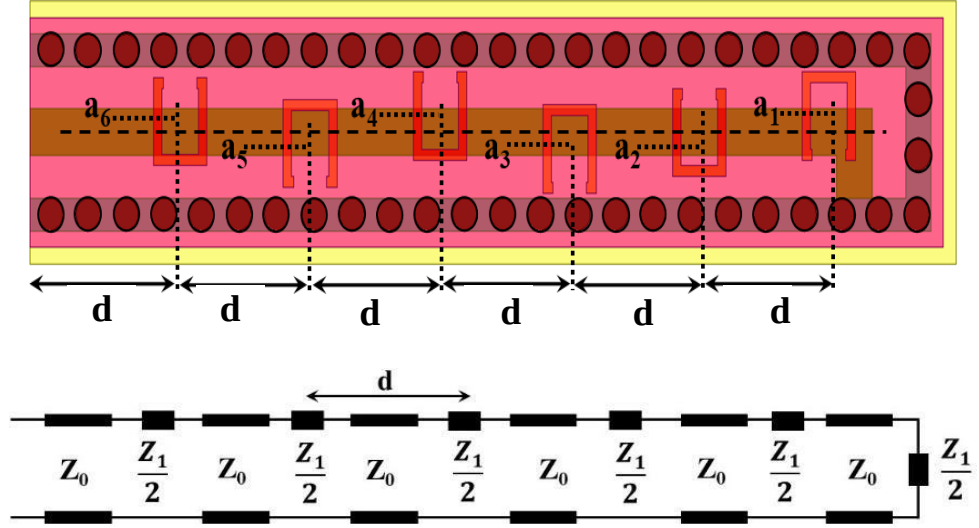


Figure 4.9: (a) Geometry in top view, and (b) equivalent circuit of the proposed 6 x 1 C-shaped double slot antenna sub-array. Dimensions (in mm): $a_1 = 0.3$, $a_2 = 0$, $a_3 = 0.3$, $a_4 = 0.3$, $a_5 = 0.2$, $a_6 = 0.2$, $d = 3.1$, $p = 3.6$.

wavelength ($\lambda_g/4$) distance (c) from the shorted end as shown in Fig. 4.8(b). To accommodate $\lambda_g/2$ slot over the SICL transmission line, a C-shaped slot is chosen. The width of the slot is 0.2 mm. In addition to the single C-shaped slot on the top plate, replicating the slot on the bottom plate makes the fundamental element of the antenna array the double C-shaped slot radiator. The dimension of the double slot radiator is tuned to resonate at the same frequency as that of the single slot radiator. The slot is kept at a distance of half-wavelength (p) from the source to maintain the same impedance at the source. To accommodate 180° out of phase current in the slots, the double slot radiator is repeated with successive opposite orientation to form 6 x 1 C-shaped slot antenna sub-array. The inter-element spacing between the slots (d), offset (a_i) of the individual slots and the slot opening or gap (g) are tuned to have in-phase excitation in all the slots. Four such sub-array are placed side by side to make 6 x 4 planar array.

Hence, the distance between successive sub-array is less than $\lambda_g/2$. The 6 x 1 slot antenna sub-array and its equivalent circuit is shown in Fig. 4.9. Because of high mutual coupling between the slots, the input impedance does not match to 50Ω . As the number of slots increases the equivalent admittance as sum of all slot admittances, approaches $1/50 \Omega$ and ultimately matches to 50Ω input port impedance. SICL based one to four way power divider feeds the 6 x 4 antenna array. The dimension of the proposed SICL based 6 x 4 C-shaped slot antenna array is 13.8 mm x 32 mm.

4.2.2.2 Parametric Analysis

The dimensions of single C-shaped slot radiator on the top plate of SICL transmission line is chosen to resonate at 25.16 GHz with a gain of 3.68 dBi. With similar dimensions, a double C-shaped slot radiator on the top and bottom plates of the SICL line is designed as shown in Fig. 4.8(b) and tuned to resonate at 25.26 GHz and gain 3.3 dBi.

A. Parametric for double C-shaped slot antenna

The single C-shaped slot positioned at quarter wavelength from the shorted end is offset from its centre position towards the via section. The offset (a) in slot towards the via wall affects impedance matching with a shift in resonance as shown in Fig. 4.10(a). As offset (a) increases the coupling of the slot decreases. An increase in C-shaped slot opening (g) controls the matching and shifts the resonance towards the higher frequency as depicted in Fig. 4.10(b). As the opening gap (g)

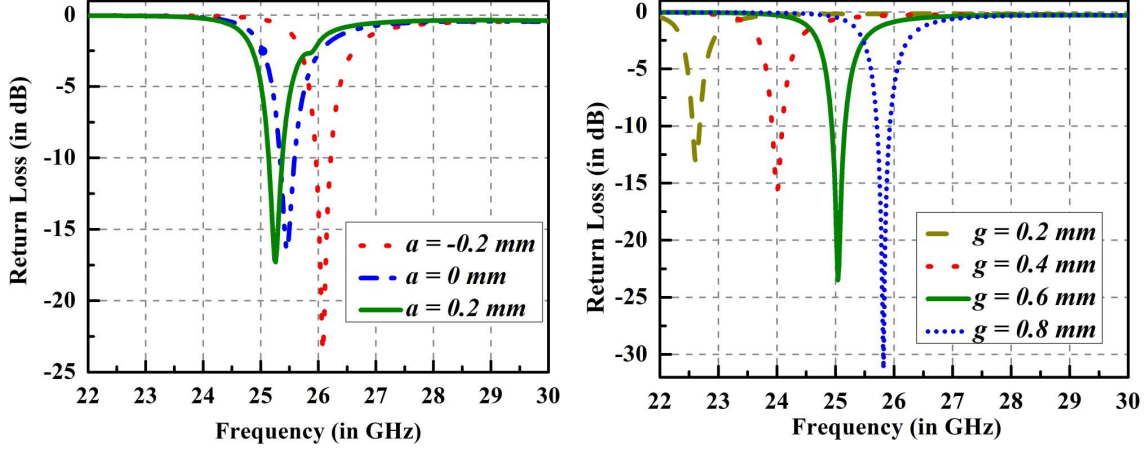


Figure 4.10: Variation in reflection coefficient with (a) offset a , and (b) slot opening g for a double C-shaped slot antenna.

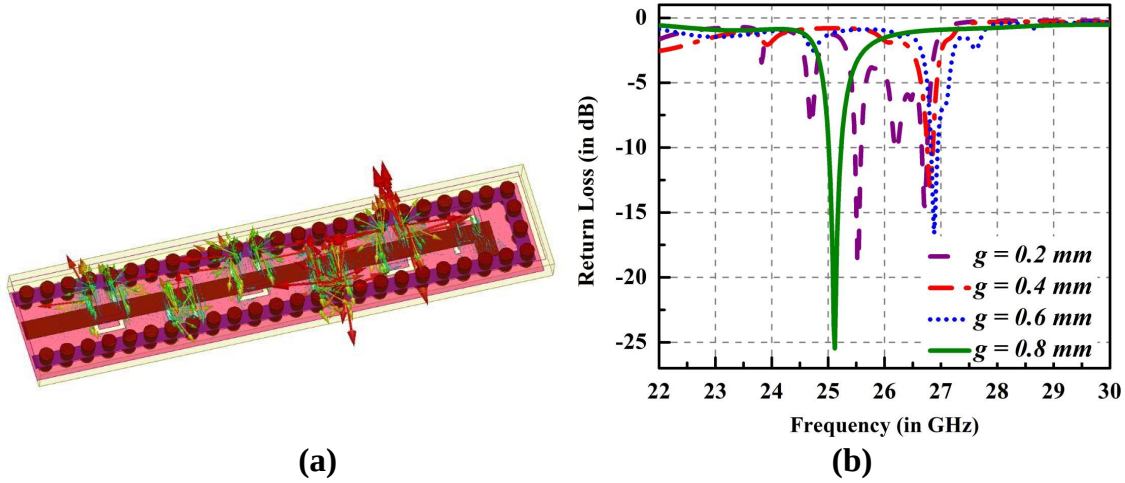


Figure 4.11: (a) Surface current density in the top and bottom plate containing the slots at 25.12 GHz and (b) variation in reflection coefficient with slot opening g of the proposed 6 x 1 C-shaped double slot antenna sub-array

increases, the effective length of the slot decreases and hence the resonant frequency increases.

B. Parametric for 6 x 1 C-shaped double slot antenna subarray

The offset in the slot is dependent on the mutual coupling existing between the i th slot with all the other slots. Hence, offset of all the slot (a_i) has been tuned to excite all the slots in-phase as shown by the surface current density in the top and bottom plate of 6 x 1 C-shaped slot antenna sub-array in Fig. 4.11(a). The mutual coupling between the slots de-tune its resonant frequency which can be re-adjusted by tuning (g) as shown in Fig. 4.11(b). This is because of the fact that slot opening (g) controls the amount of current in the radiators. Due to the loading effect of the slots in the series fed array, the inter-element spacing (d) needs to be adjusted. It is observed that as the number of double slot radiator increases from 2 to 6 in the sub-array, (d) is required to be tuned from 2.3 mm to 3.1 mm.

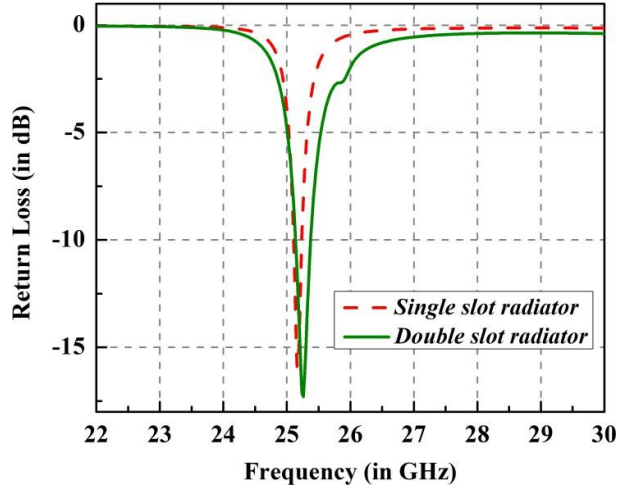


Figure 4.12: Reflection coefficient of the proposed single and double C-shaped slot antenna.

4.2.3 Results

The single C-shaped slot radiator resonates at 25.16 GHz as shown in Fig. 4.12 with a gain of 3.68 dBi. Its radiation pattern is shown in Fig. 4.13(a-b). The fundamental double slot antenna resonates at 25.26 GHz as shown in Fig. 4.12 with gain of 3.3 dBi. The radiation pattern is shown in Fig. 4.13(c-d). A dual beam is observed as expected with co-pol component 22.8 dB above the cross-pol component. 6 x 1 C-shaped double slot antenna sub-array exhibits a gain of 7.5 dBi with co-pol component 25.8 dB above the cross-pol component. The radiation pattern of the 6 x 1 antenna sub-array is shown in Fig. 4.15(a-b). 6 x 4 C-shaped double slot antenna array produces

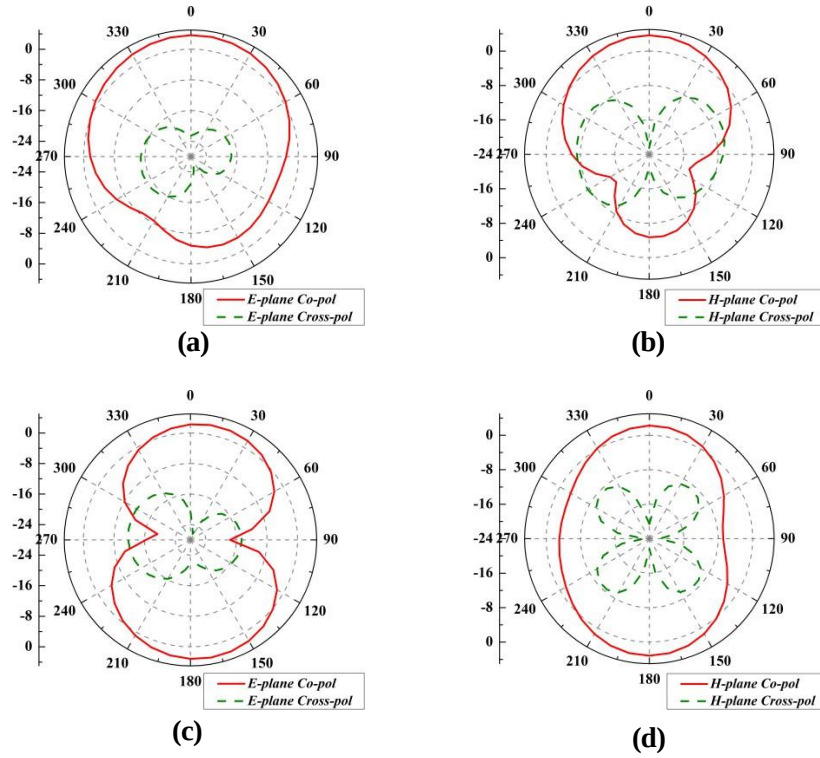


Figure 4.13: Radiation pattern of single slot (a-b) at 25.16 GHz and fundamental double slot radiator (c-d) at 25.26 GHz in $\phi = 0^\circ$ and $\phi = 90^\circ$ cut planes respectively.

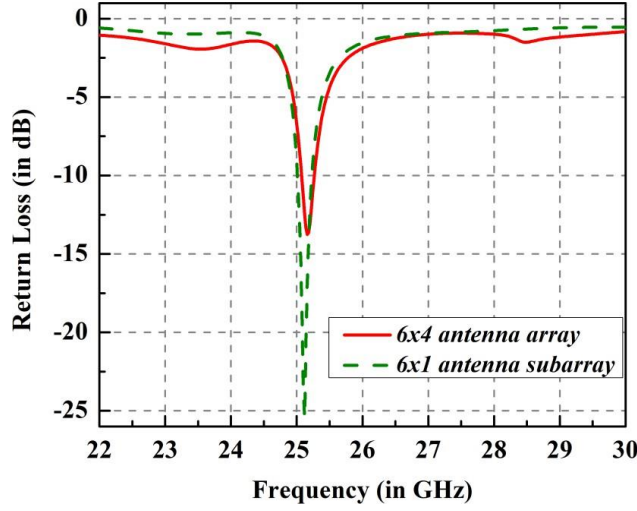


Figure 4.14: Reflection coefficient of the proposed 6 x 1 C-shaped slot antenna sub-array and 6 x 4 C-shaped slot antenna array.

a high gain of 9.87 dBi with co-pol component 19.6 dB above the cross-pol component. The array scans 3 dB beamwidth of 46° . The radiation pattern of 6x4 slot antenna array is plotted in Fig.

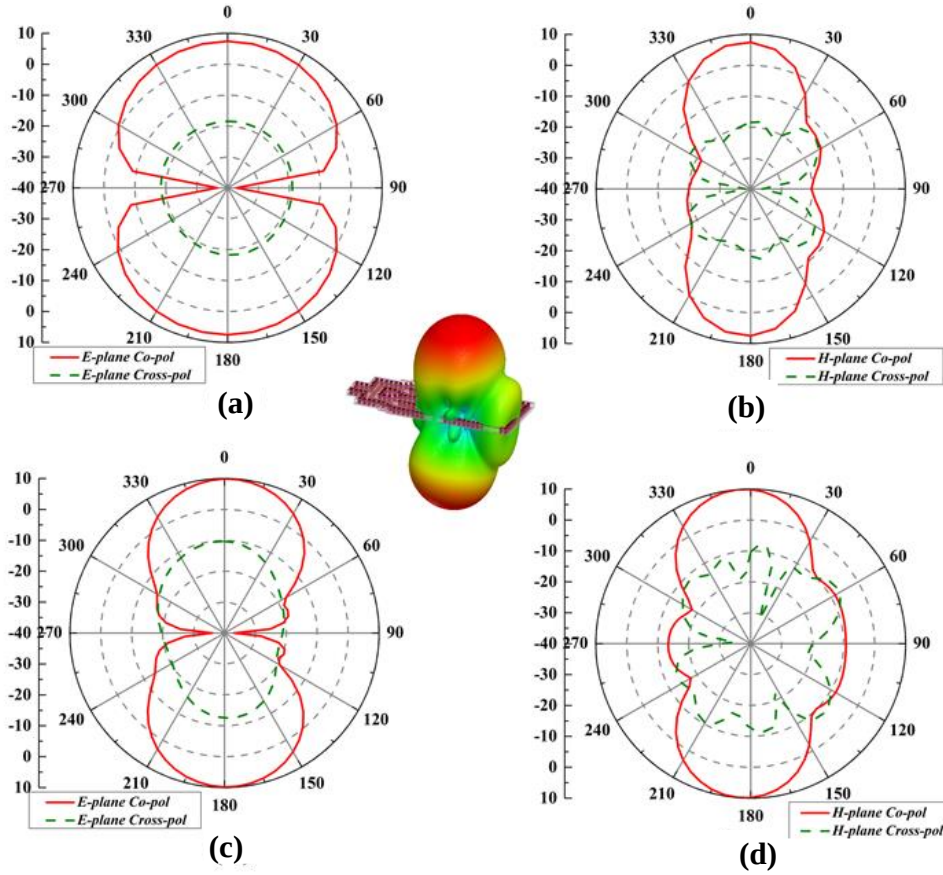


Figure 4.15: Radiation pattern of the proposed 6 x 1 C-shaped slot antenna sub-array (a-b) at 25.12 GHz and 6 x 4 C-shaped slot antenna array (c-d) at 25.16 GHz in $\phi = 0^\circ$ and $\phi = 90^\circ$ cut planes, inset 3D radiation pattern of the 6 x 4 C-shaped slot antenna array.

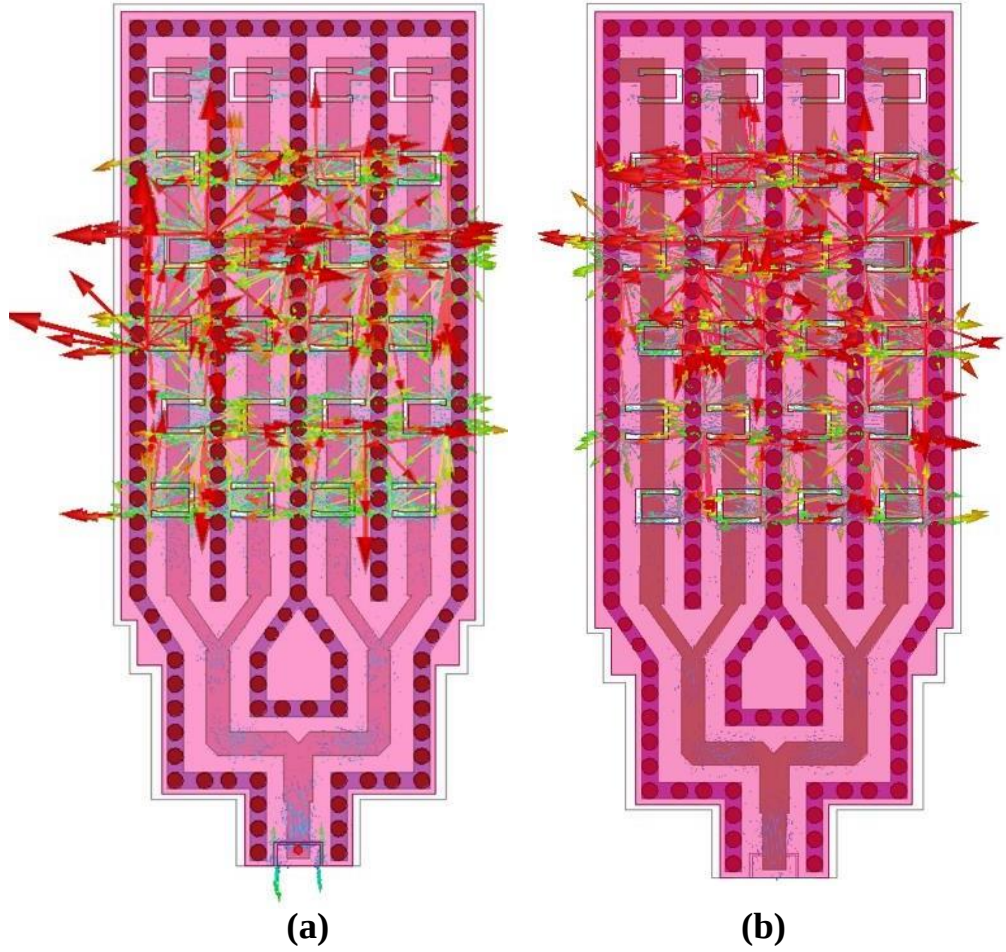


Figure 4.16: Surface current density at 25.16 GHz in the (a) top and (b) bottom plate of the proposed SICL based 6 x 4 C-shaped double slot antenna array.

4.15(c-d). The surface current plotted on the top and bottom surface of the 6x4 slot antenna array is shown in Fig. 4.16, affirming all the slots being excited in the same phase. A sidelobe level of -18.27 dB and front to back ratio (FTBR) of 20.16 dB is obtained in the SICL based 6x4 C-shaped slot antenna array.

The study of slot antenna array and its performance analysis over SICL transmission line proves effectiveness of SICL in making compact high gain antenna array. However, due to high quality factor (Q) of the SICL structure, narrow bandwidth is obtained in the proposed designs.

4.3 SICL Excited Dual Band Crossed Dipole Uniform Array For Endfire Applications

This section presents a novel technique to implement crossed dipole antenna fed by Substrate Integrated Coaxial Line (SICL) technology. Traditional crossed dipole design requires side-by-side arrangement of orthogonal dipole antennas which make them occupy much space. Moreover, the L-probe used to feed the antennas make them non-planar. In this work, a SICL fed planar crossed dipole antenna is proposed. The proposed design uses stacked configuration of orthogonal dipole antennas instead of side-by-side arrangement, that results in the compact footprint of the antenna.

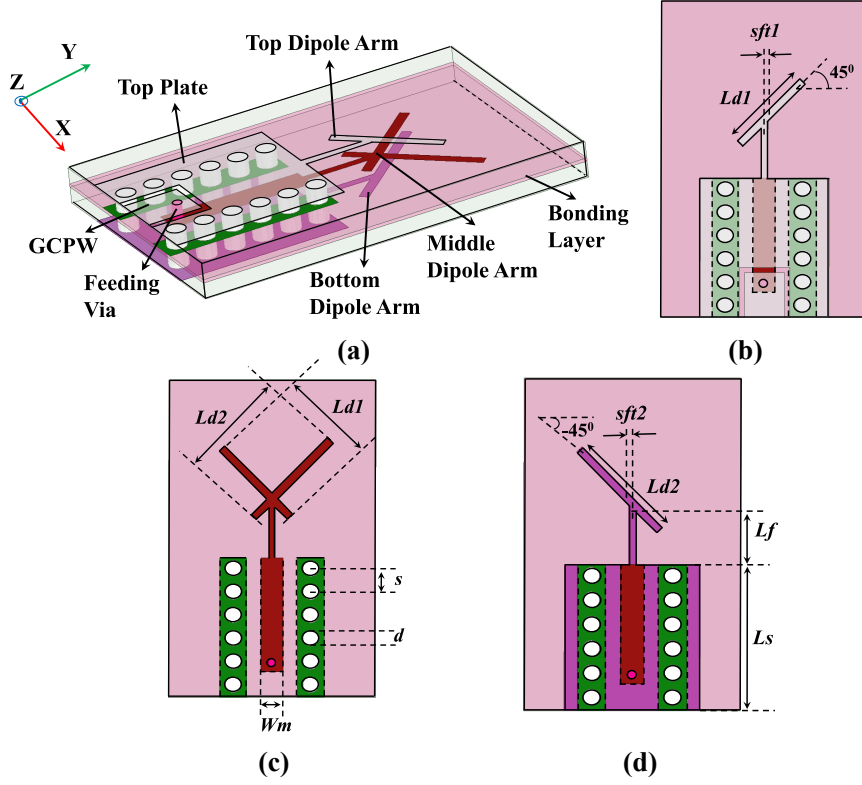


Figure 4.17: (a) 3D trimetric view and layerwise configuration in (b) top layer, (c) middle layer and (d) bottom layer of the proposed SICL fed crossed dipole antenna.

The dimensions are (in mm) : $sft1 = 0.4, Ld1 = 3.45, Ld2 = 4.1, sft2 = 1.0, Lf = 1.8, W_m = 0.86, s = 0.9, D = 0.6$.

This work explains the step by step procedure to design the crossed dipole antenna with much simpler excitation of the two dipole antennas. The inherent advantage of out of phase surface current of the SICL transmission line is utilized efficiently to excite the two dipole antennas. The crossed dipole is implemented to obtain dual band response at 26 GHz and 28 GHz. Two $\pm 45^\circ$ inclined dipoles are printed on the top/bottom of the substrate and simultaneously fed by top/bottom plate of the SICL line. The other arm of the dipole is printed in between the two substrate of the SICL line and is excited by the middle strip of the SICL line. A SICL 1:4 power divider is employed to feed four crossed dipole antenna to form an array.

4.3.1 Design and Working Principle

The proposed antenna is designed using two Taconic TLY-5A substrate 8 mm x 12.5 mm (height of 0.5mm each, $\epsilon_r = 2.2$) and bonded together using Taconic FR-28 bond layer (height 0.1 mm, $2.75 < \epsilon_r < 2.9$) to form a planar structure for the basic antenna element. Grounded Coplanar Waveguide (GCPW) to Substrate Integrated Coaxial Line (SICL) transition is implemented to excite the TEM mode in the feed network [Baghel and Mukherjee, 2020a].

4.3.1.1 SICL fed Modified Single Dipole Antenna

The first 45° inclined dipole is printed on the top substrate and is fed by top plate of the Substrate Integrated Coaxial Line (SICL) line. The other arm of the dipole is printed in between the two substrate of the SICL line and is excited by the middle strip of the SICL line as shown in Fig. 4.17(a). This antenna operates at 28 GHz. Following the similar analogy, the second dipole

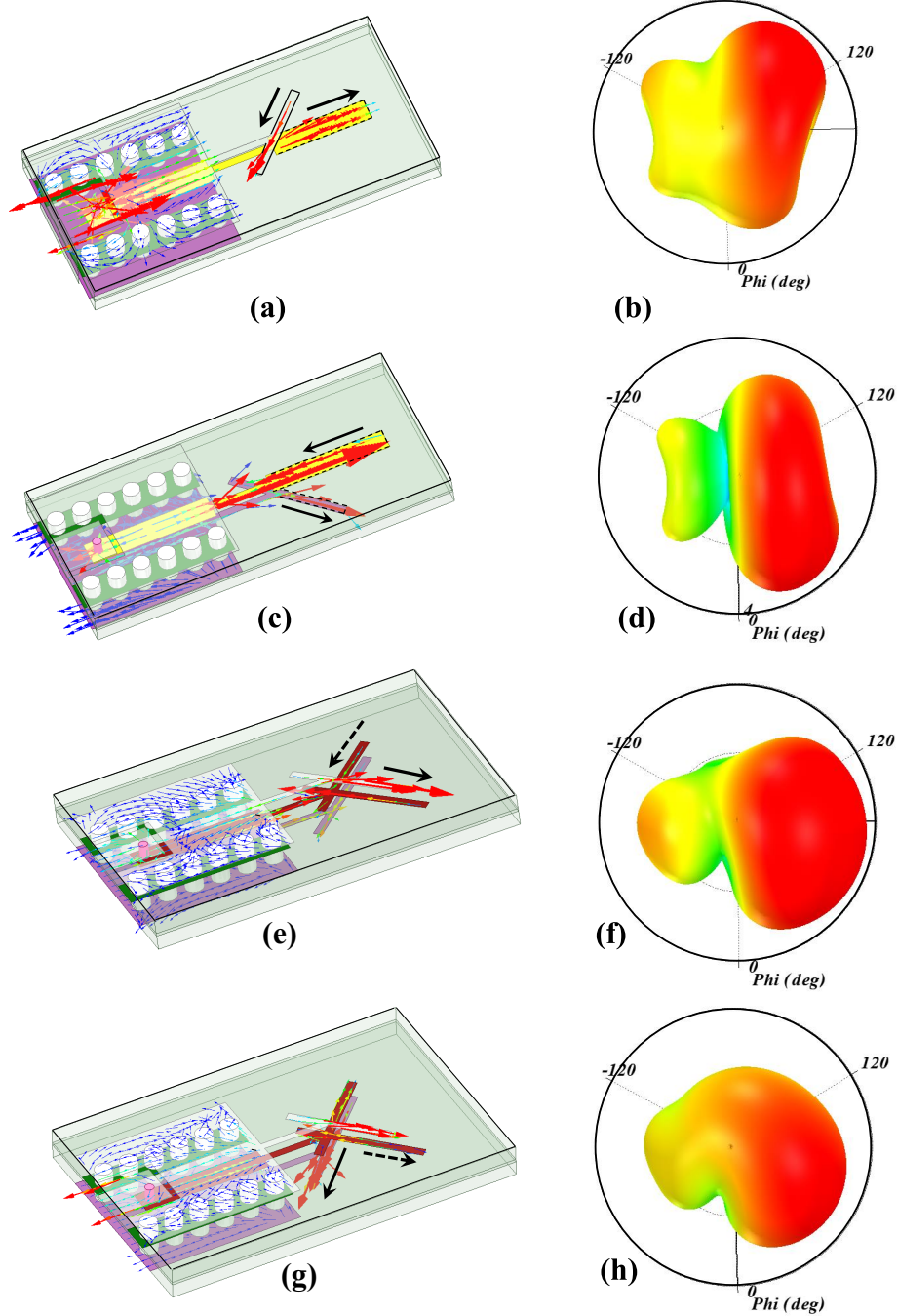


Figure 4.18: (a) 3D trimetric view and layerwise configuration in (b) top layer, (c) middle layer and (d) bottom layer of the proposed SICL fed crossed dipole antenna. The dimensions are (in mm) : $sft1 = 0.4$, $Ld1 = 3.45$, $Ld2 = 4.1$, $sft2 = 1.0$, $Lf = 1.8$, $W_m = 0.86$, $s = 0.9$, $D = 0.6$.

-45° inclined dipole is printed on the bottom substrate and is fed by the bottom plate of the SICL line. The lengths of the antenna ($Ld1$, $Ld2$) and the offsets ($sft1$, $sft2$) in center position is tuned to operate at 26 GHz and 28 GHz. The antenna is termed modified here as it is different from the conventional dipole antenna fed by SICL [Baghel and Mukherjee, 2018b].

4.3.1.2 Principle of Operation

To understand the working principle of the crossed dipole antenna fed by Substrate Integrated Coaxial Line (SICL), consider a single 45° dipole antenna fed by the respective plate of the SICL line as shown in Fig. 4.18. First to design the dipole antenna at 26 GHz, a dipole antenna is formed by the 45° inclined dipole placed on the top substrate and is fed by the top plate of the SICL. Surface current plotted in Fig. 4.18(a) shows the excitation of the top dipole antenna. The 180° out of phase current between the top and the middle plate of the SICL is utilized to excite the two arms of the dipole antenna. A slight tuning in the length of the dipole arm $Ld1$ and offset $sft1$ is employed to tune the resonant frequency at 26 GHz. The resulting radiated beam is oriented along the top dipole antenna as shown in Fig. 4.18(b). Following the similar analogy, the second -45° inclined dipole arm is printed on the bottom substrate and is fed by bottom plate of the SICL alone in the absence of the top dipole antenna. The dipole arm length $Ld2$ and offset $sft2$ from the center position is tuned to operate the antenna at 28 GHz. Fig 4.18(c) shows the surface current along the second dipole antenna operating at 28 GHz and Fig. 4.18(d) shows orientation of the radiated beam along the -45° inclined dipole. The other arm connected to the middle plate is kept straight to serve as the common middle arm having same current distribution for the two dipole antennas.

To implement the proposed crossed dipole antenna, the top 45° inclined dipole antenna is combined with the bottom -45° inclined dipole antenna and are fed by the top and bottom plate of the Substrate Integrated Coaxial Line (SICL) transmission line respectively. To maintain similar current distribution in the two dipole antennas, two middle arm are implemented at $\pm 45^\circ$ as shown in Fig. 4.17(c). The surface current depicted in Fig. 4.18(e) at 26 GHz denotes the excitation of top 45° inclined dipole arm and the middle -45° inclined dipole arm. Thus the constructive interference from the dipole creates radiated electromagnetic (EM) wave along the endfire direction as shown in Fig. 4.18(f). Similarly, the excitation of bottom -45° inclined dipole arm and the middle 45° inclined dipole arm is shown in Fig. 4.18(g). This configuration enables constructive interference of the wave and the beam is radiated along the endfire direction as shown in Fig. 4.18(h).

4.3.1.3 SICL fed 1 to 4 way Power Divider

To implement the array for stable radiation pattern, a 1:4 power divider is implemented in SICL as shown in Fig. 4.19(a). The performance of the power divider is expressed in Fig. 4.19(b). A marginal phase difference of 0.15° is observed between the output ports.

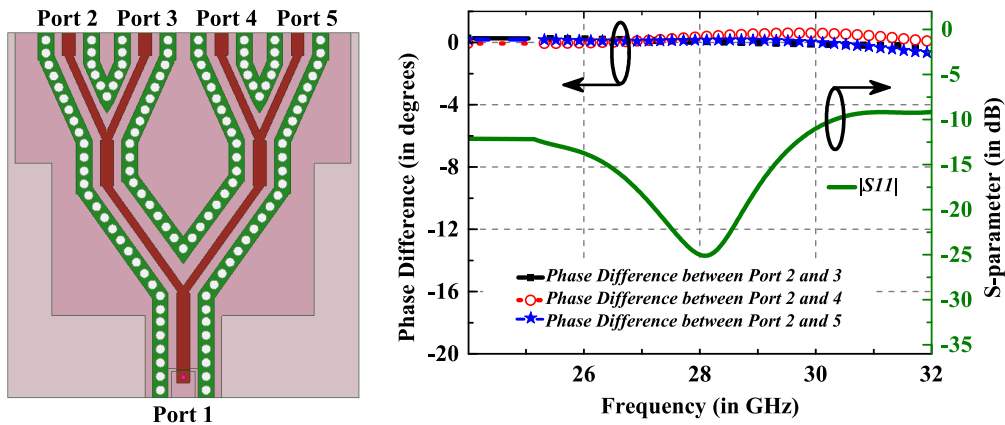


Figure 4.19: (a) Top view and (b) performance of the proposed SICL fed 1 to 4 way power divider.

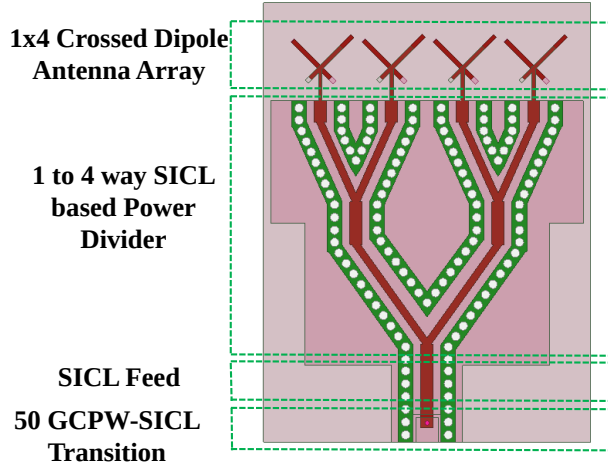


Figure 4.20: Top view of the proposed SICL fed 1x4 Crossed Dipole Antenna Array for dual band endfire applications.

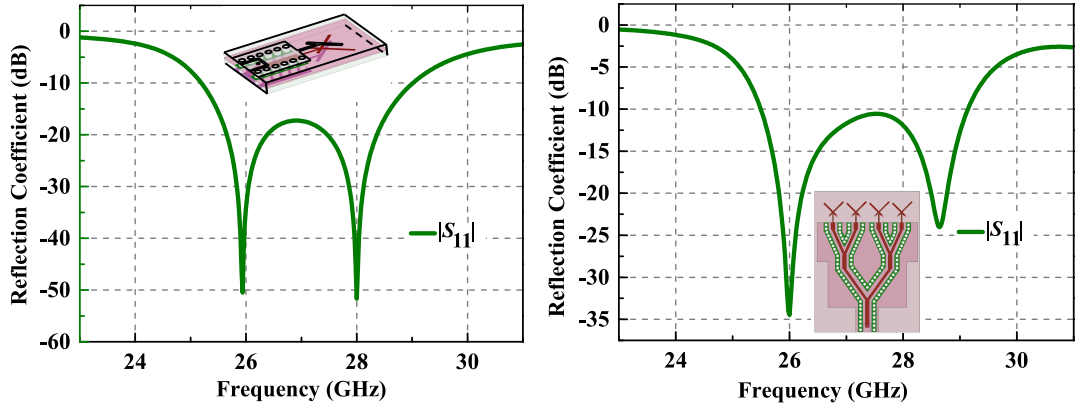


Figure 4.21: Reflection Coefficient for the proposed dual band SICL fed (a) crossed dipole antenna and (b) 1 x 4 crossed dipole antenna array.

4.3.1.4 SICL fed 1x4 Crossed Dipole Antenna Array

A 1x4 antenna array is formed by placing four crossed dipole antenna with a center to center spacing of 5 mm as shown in Fig. 4.20. The feeding network of the array consists of a Grounded Co-planar Waveguide (GCPW) to Substrate Integrated Coaxial Line (SICL) transition and 1 to 4 equal power divider. The length of the feed line is tuned to have proper impedance match. The lengths of the dipole arms and the offset are tuned to have the resonance for accommodating the two operating frequencies.

4.3.2 Results and Discussion

The simulated reflection coefficient for the dual band crossed dipole antenna and 1 x 4 crossed dipole antenna array is shown in Fig. 4.21. The proposed antenna operates at 26 GHz and 28 GHz exhibiting a wide impedance bandwidth from 25.3 to 28.7 GHz. The antenna array exhibits a wider impedance bandwidth from 25.3 to 29.1 GHz. The antenna array exhibits a shift in the upper resonant frequency as shown in Fig. 4.21(b) due to the mutual coupling between the dipole antenna. The surface current and electric field distribution for the array is plotted in Fig. 4.22 at the center frequency. The dipole antenna elements are successfully excited by the SICL

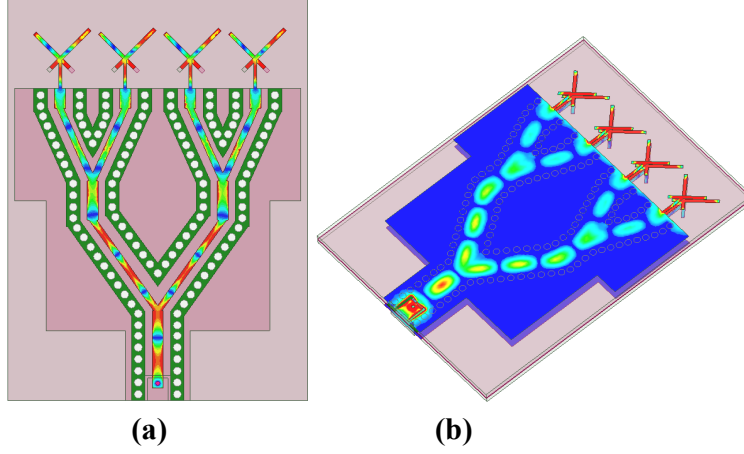


Figure 4.22: (a) Surface current and (b) electric field distribution of the proposed SICL fed 1x4 Crossed Dipole Antenna Array.

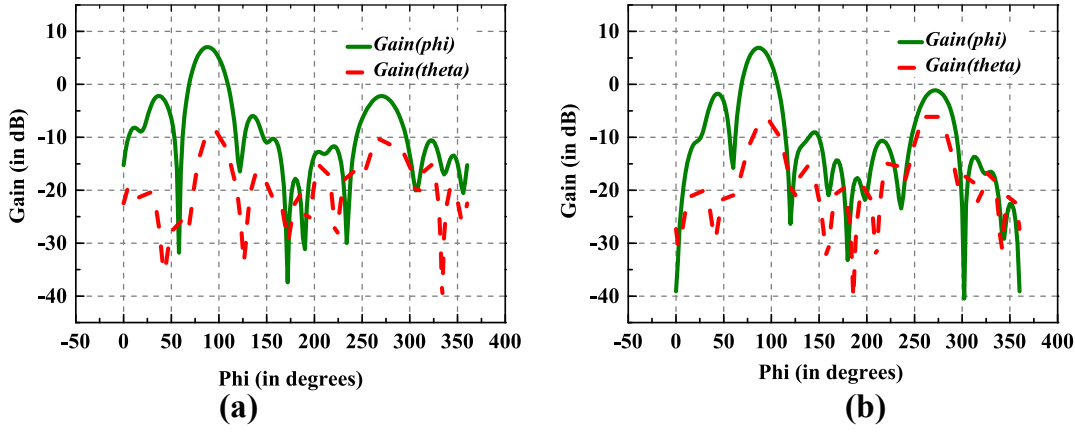


Figure 4.23: Radiation pattern of the proposed SICL fed 1x4 Crossed Dipole Antenna Array at (a) 26 GHz and (b) 28 GHz.

based power divider with equal current distribution. To examine the performance of the array, the radiation pattern is plotted in the endfire direction for the two desired frequencies 26 GHz and 28 GHz as shown in Fig. 4.23. A sidelobe level of -13 dB is achieved in the proposed antenna array. However, there is a rise in left side lobe which is attributed by the strong mutual coupling between the arms of the crossed dipole antenna elements of the array. The array exhibits a gain of 9.7 dBi and 10 dBi at 26 GHz and 28 GHz respectively with wide impedance bandwidth of 3.1 GHz. The cross polarization level better than 20 dB and Front-to-Back Ratio (FTBR) better than 17 dB is obtained for the proposed design.

SICL is useful in enabling stacked arrangement of dipole within its substrates. High gain and better cross polarization level (>20 dB) with high Front-to-Back Ratio better than 17 dB encourages its application in the 5G millimeter wave frequency spectrum.

4.4 Substrate Integrated Coaxial Line (SICL) based Millimeter Wave Switching Board and its Application for Antenna Arrays

In order to cater the Ultra Reliable and Low Latency (URLLC) needs of 5G mmWave communication, it is necessary to achieve fast switching between the different polarization states. Electrical technology employing switches to turn ON/OFF the feed networks for simultaneously dynamic redistribution of the current, presents a viable and practical solution. SICL provides the advantage over SIW technology for mounting SMD components for different applications. The integration of RF components over the SIW is difficult due to the single-conductor based structure of SIW. While SICL being the two-conductor transmission line provides ease of integration of RF components in planar technology as presented in this section.

4.4.1 Substrate Integrated Coaxial Line (SICL) based Switching Board

The design of a switching board for mmWave frequency with RF switches possess significant difficulty and therefore has not been addressed in literature so far. This work presents the first implementation of SICL based switching board using RF switch directly over the SICL transmission line in the same substrate. In order to highlight the benefits of SICL technology, a three port SPDT switch is configured in SICL which is otherwise difficult in its counter part technology. The performance of the designed SICL switching board encourages its utilization in practical 5G scenarios. Thereby two applications of the proposed SICL switching board is utilized for designing a dual polarization antenna array and pattern reconfigurable antenna array for FR2 n257 wideband.

4.4.1.1 Development of SICL based Switching Board

Dual state reconfigurability in the presented work is provided using a SPDT switch. A Substrate Integrated Coaxial Line (SICL) based board is designed to control the polarization state using a SPDT switch. The switch is suitable for 5G applications (24-32 GHz), providing low insertion loss of 1.1 dB. The RF input (RFC) and output ports (RF1, RF2) of the SPDT switch is connected to the 50 Ω SICL feed lines using a small biasing pads over which the switch is mounted.

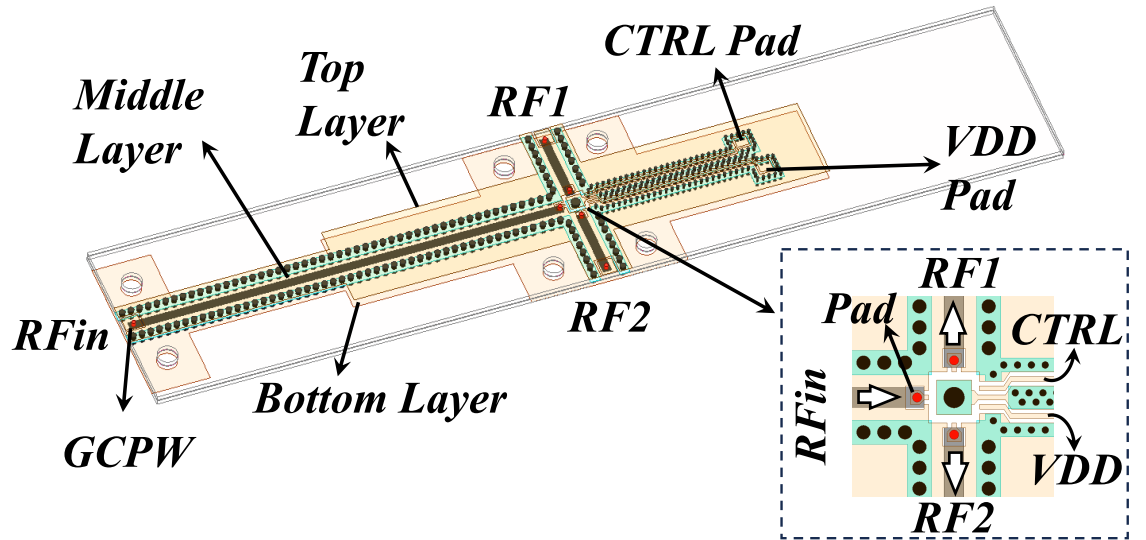


Figure 4.24: Design of the proposed SICL based switching board, inset: pads for RF switch.

The top layer of SICL acts as ground plane for the switch and the ground pins of the switch are directly mounted on the SICL feed section. To supply a 3.3 V supply voltage to power ON the RF switch, a 0.2 mm trace is etched that connects to the VDD pin of the switch. The switching between output ports (RF1, RF2) is controlled by the CTRL pad that supplies DC voltage to the CTRL pin of the switch. A 100 pF bypass capacitor is mounted on the supply trace that filters the high frequency noise. The design of the SICL based board is shown in Fig. 4.24. When the DC supply is turned ON ($V_{DD} = 3.3$ V) and 0 V control is provided, RF output is obtained at port RF1 and RF2 is turned OFF. Alternately, when control pin is set to 3.3 V, output port RF2 is turned ON and RF1 is turned OFF. The designed board provides 35 dB isolation with low insertion loss of 1.7 dB.

4.4.1.2 Results and Discussion

The fabricated prototype of the SICL based switching board is shown in Fig. 4.25(a). The Silicon SPDT Reflective Switch ADRF5300 by Analog Devices is mounted on the SICL board and bypass capacitor (TDK, C1005NP01H101J050BA) is mounted on the DC supply trace connected to VDD pad. The performance of the switch in OFF (CTRL = 0 V) and ON (CTRL = 3.3 V) state is shown in Fig. 4.25(b) & (c). The proposed switch board works well in the frequency range 24 - 32 GHz. The board shows an insertion loss below 3.2 dB and isolation better than 30 dB in the frequency of interest.

Next, in the further sections we introduce the novel on-board integration of this RF switch to control the polarization reconfigurability and pattern reconfigurability, signifying the first attempt of such implementation.

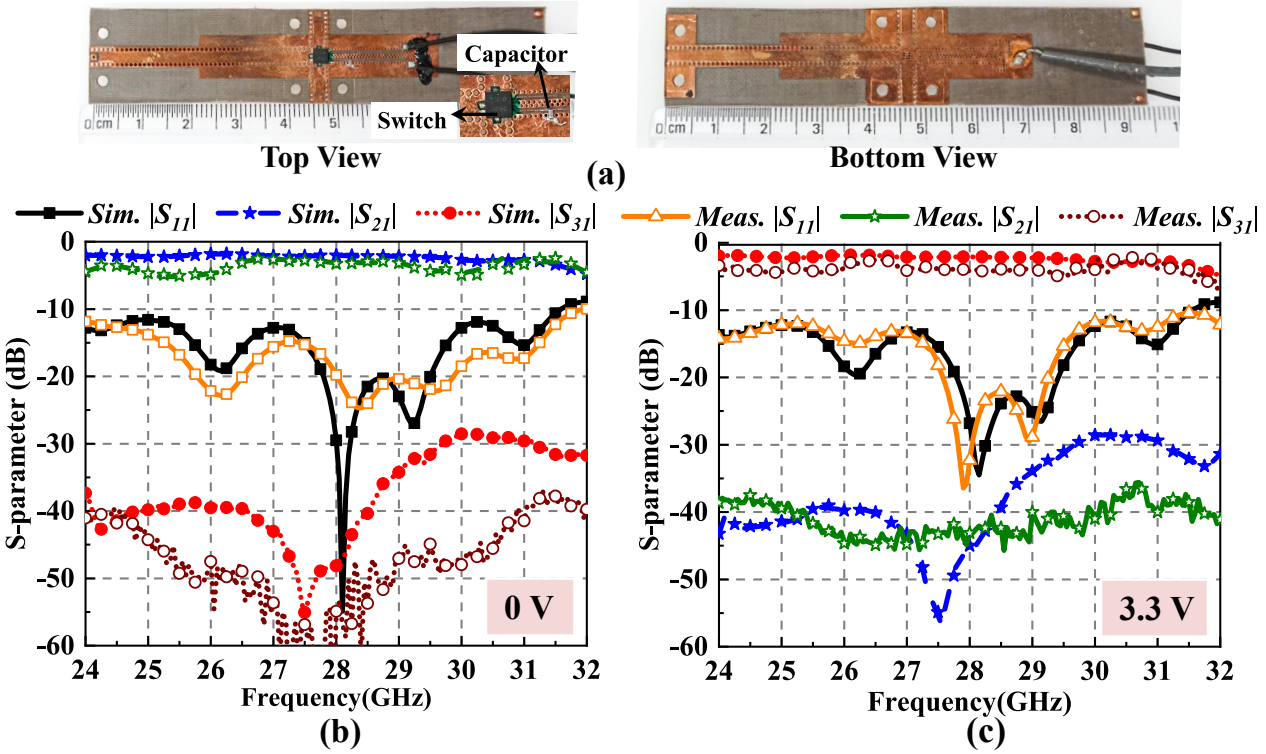


Figure 4.25: (a) Design of the proposed SICL based switching board in top and bottom view. S-parameter plot of the designed switching board for (b) OFF state (CTRL = 0 V) and (c) ON state (CTRL = 3.3 V).

4.4.2 SICL based Reconfigurable Dual Linearly Polarized Wideband Antenna Array for 5G Millimeter Wave Applications

A SICL based switching board utilizing a low loss SPDT RF switch is presented in the previous section. This study introduces a dual polarized reconfigurable antenna array designed specifically for 5G FR2 millimeter wave frequencies utilizing the proposed SICL based switching board. The intermediate layer of the Substrate Integrated Coaxial Line (SICL) is utilized to excite a triangular patch antenna at 27 GHz. In order to achieve complete n257 FR2 band operation, a parasitic triangular patch is included. This additional patch resonates at a frequency of 29 GHz and possesses an identical field distribution to that of the directly fed triangular patch. The proposed antenna configuration thereby achieves a broad bandwidth of 3.5 GHz with peak gain of 5.7 dBi. To achieve polarization reconfigurability, a SICL based novel switching board utilizing a low loss SPDT RF switch is introduced in the presented work. Polarization reconfigurability is attained by the utilization of digital control on the SICL based switching board to stimulate two alternate antenna arrays at distinct time intervals. This system utilizes Half Duplex communication employing the Time Division Duplex (TDD) technique, which is one of the standard method for operating at 5G FR2 frequencies. The proposed antenna array provides wide bandwidth of 28.57 % at 28 GHz with an average stable gain of 15.5 dBi. This work is suitable for dual polarized 5G mmWave applications.

4.4.2.1 Design

A. Development of Broadband Triangular Patch Antenna

A regular triangular patch antenna is designed with side arm length of approximately half wavelength using formulations stated in [Kumprasert and Kiranon, 1994]. The antenna design and

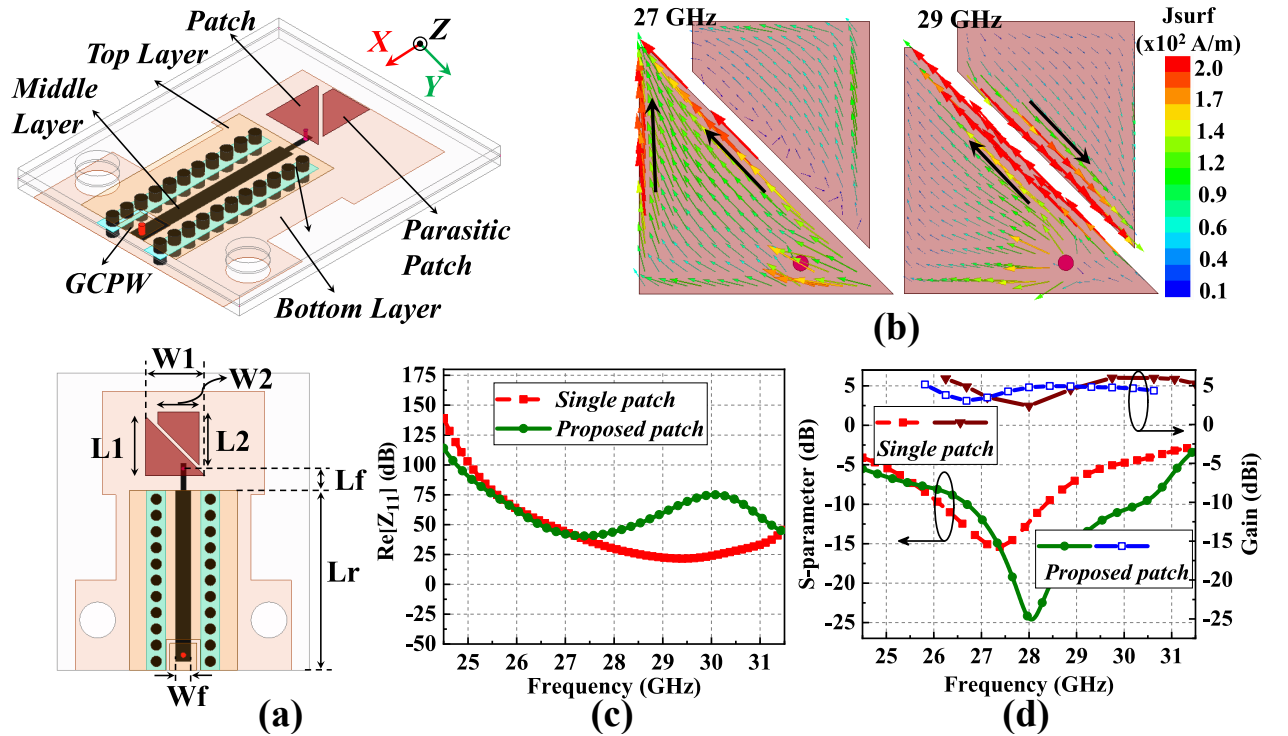


Figure 4.26: (a) Design of the proposed SICL fed triangular patch antenna and its dimensions, (b) current distribution in the patch, (c) real $[Z_{11}]$ plot and (d) reflection coefficient of the proposed antenna. The dimensions are (in mm) : $L1 = 3.8$, $W1 = 3.6$, $L2 = 2.7$, $W2 = 2.8$, $Lf = 1.7$, $Lr = 11$, $Wf = 0.85$

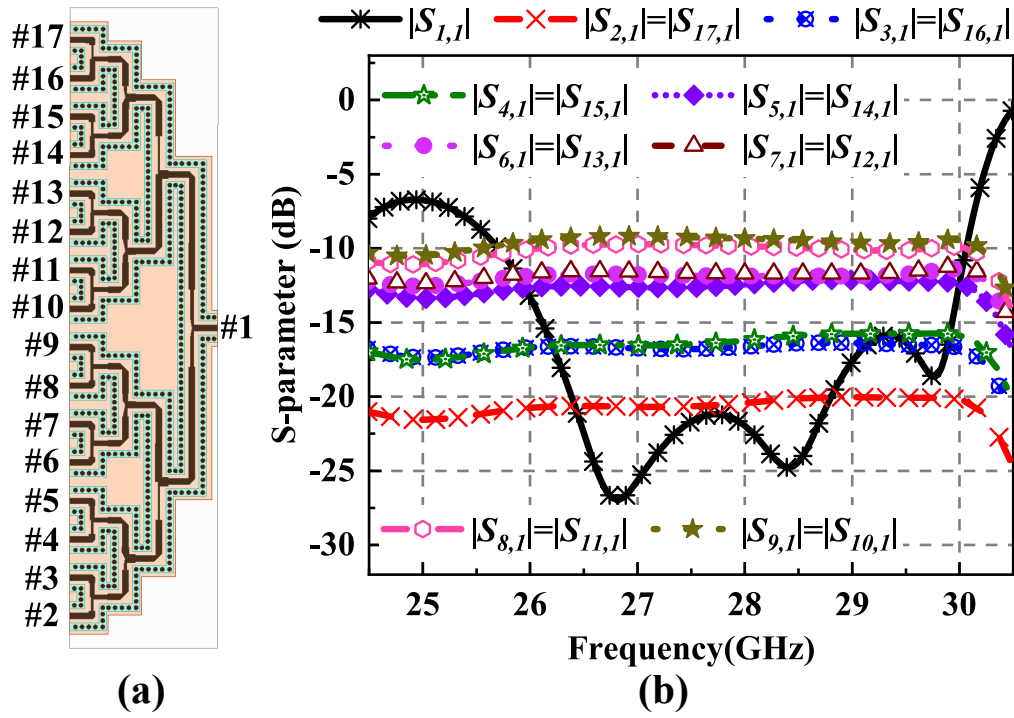


Figure 4.27: (a) Design and (b) S-parameter plot of the proposed SICL based Taylor power divider feed network.

its dimensions are given in Fig. 4.26. The ground layer of the SICL feed section is extended below the patch that behaves as bottom reflector for back radiations and thereby contributes in achieving unidirectional radiation pattern. To feed the triangular patch antenna, a SICL feed line is used. A 50Ω Grounded Co-Planar Waveguide (GCPW) to SICL transition is used to excite TEM based SICL. Triangular patch is fed by the middle layer of the SICL feed section using a small feed via as shown in the Fig. 4.26. The proposed patch under consideration offers a bandwidth of 2 GHz. To increase the bandwidth of the antenna for n257 band, a parasitic patch is introduced in the design. It is placed close to the directly fed patch to receive sufficient coupling for excitation. Fig. 4.26(b)

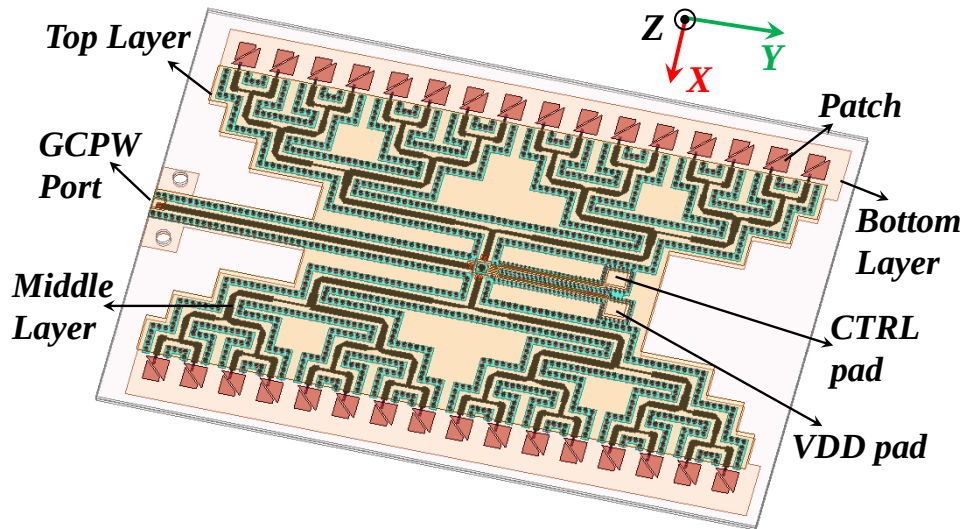


Figure 4.28: Design of the proposed SICL based reconfigurable dual polarized antenna array.

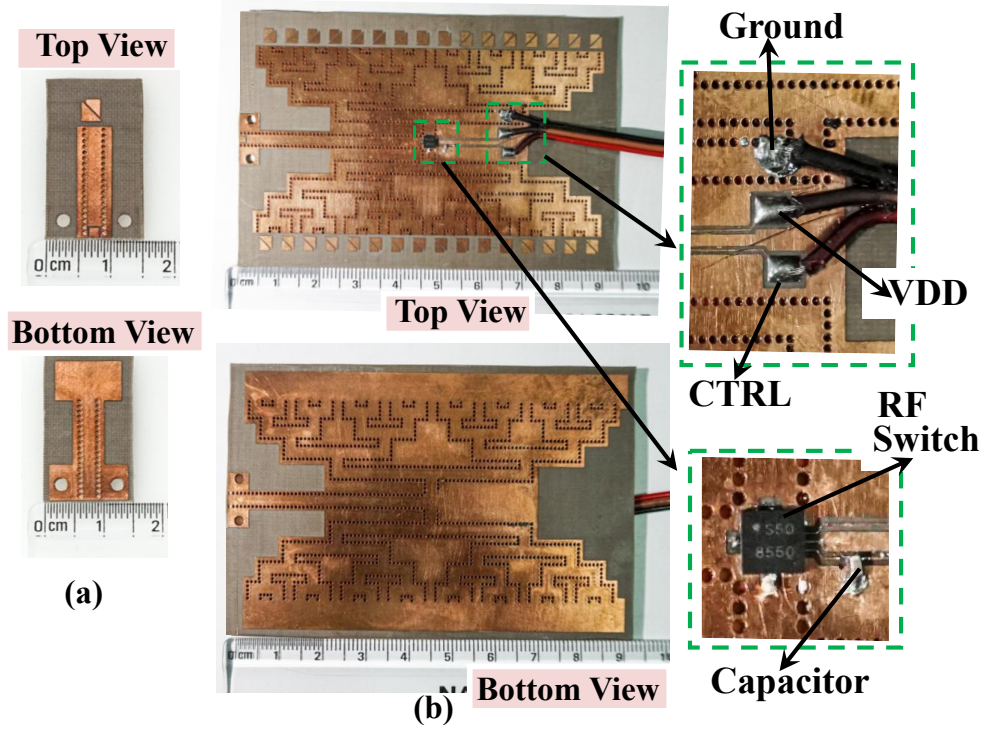


Figure 4.29: Design of the proposed prototype for (a) SICL fed triangular patch antenna and (b) SICL based reconfigurable dual polarized array. (Inset: depictions of biasing pins on pads, on-board integration of RF switch).

illustrates the surface current distribution that demonstrates the excitation of the directly excited patch at 27 GHz and the parasitic patch at 29 GHz respectively. The coupled patch configuration exhibits wider bandwidth than the single antenna as depicted by the input impedance of the antenna (obtained from de-embedding in Ansys HFSS) shown in Fig. 4.26(c). The reflection coefficient

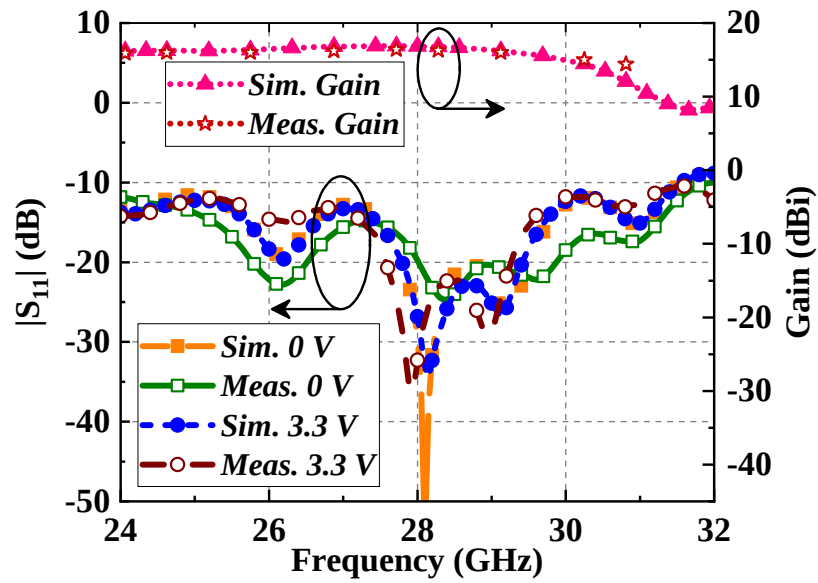


Figure 4.30: Reflection coefficient and Gain plot for the proposed SICL fed reconfigurable dual polarized antenna array.

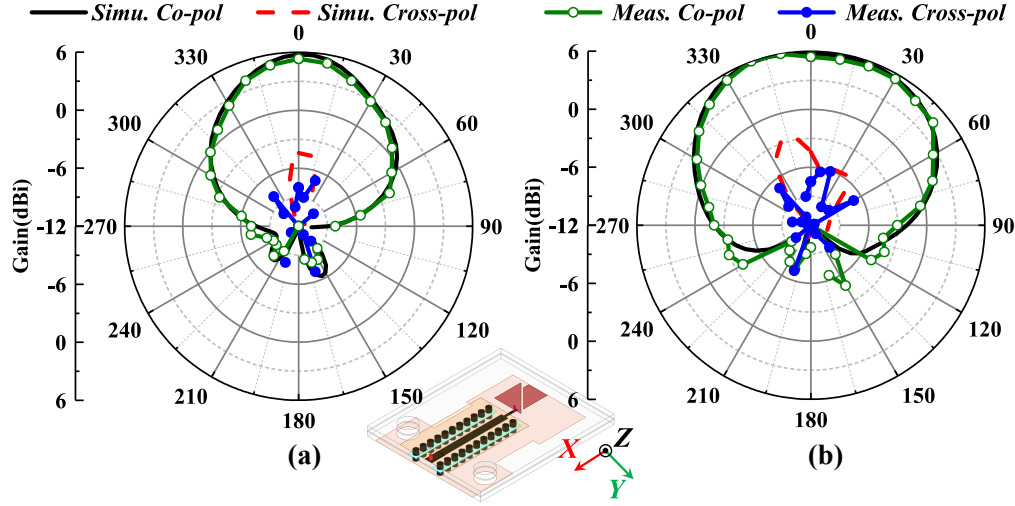


Figure 4.31: Radiation pattern at 28 GHz in E-plane ($\phi = 45^\circ$), (b) H-plane ($\phi = 135^\circ$) respectively for proposed SICL fed triangular patch antenna.

cient of the single patch and proposed coupled patch antenna configuration is shown in Fig. 4.26(d).

B. Development of SICL Low Sidelobe Taylor based Feed Network

To achieve high gain for mmWave frequencies, a 1×16 linear array of proposed triangular patch

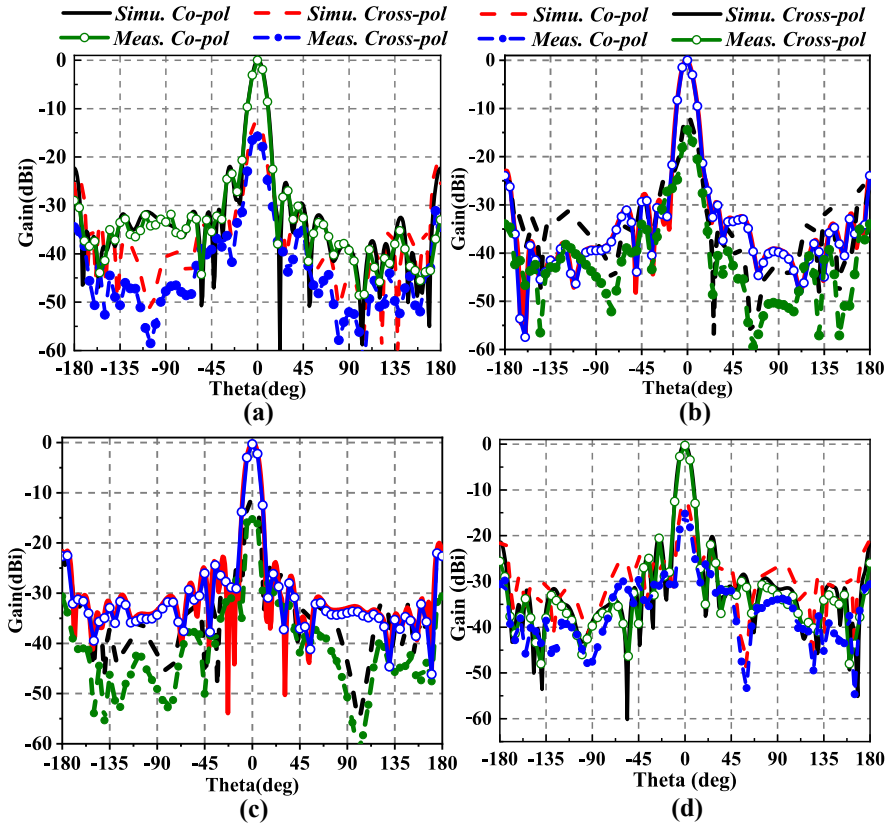


Figure 4.32: Radiation pattern in (a)-(b) at 26 GHz and (c)-(d) at 29 GHz in E-plane ($\phi = 45^\circ$) and H-plane ($\phi = 135^\circ$) respectively for OFF state (CTRL = 0 V) of the proposed dual polarized array.

antenna is designed. Taylor distribution based 1:16 way SICL power divider is designed as shown in Fig. 4.27 to achieve 30 dB sidelobe level. The designed feed network obtains wide impedance bandwidth ($|S_{11}| < -15$ dB) with nearly $\pm 5^\circ$ phase difference between the output ports throughout the bandwidth.

C. Development of SICL based Polarization Reconfigurable Antenna Array

A pair of 1×16 linear array of the proposed triangular patch fed by SICL based Taylor power divider is designed as shown in Fig. 4.27 for achieving dual linear polarization. Polarization reconfigurability is achieved in the antenna arrays by connecting it to the output RF lines (RF1, RF2) of the SICL based switching board as shown in Fig. 4.28. The orientation of the two antenna arrays fed by RF lines (RF1, RF2) as shown in Fig. 4.28 is chosen to attain orthogonal polarization in the radiated beams.

4.4.2.2 Results and Discussion

The fabricated prototype of the proposed SICL fed triangular patch and dual polarized reconfigurable antenna array is shown in Fig. 4.29. The connecting wires in the top view of the array in Fig. 6(b) are the ground (black), control (CTRL in yellow) and DC supply (red). The simulated and measured reflection coefficient of the proposed SICL fed triangular patch array is

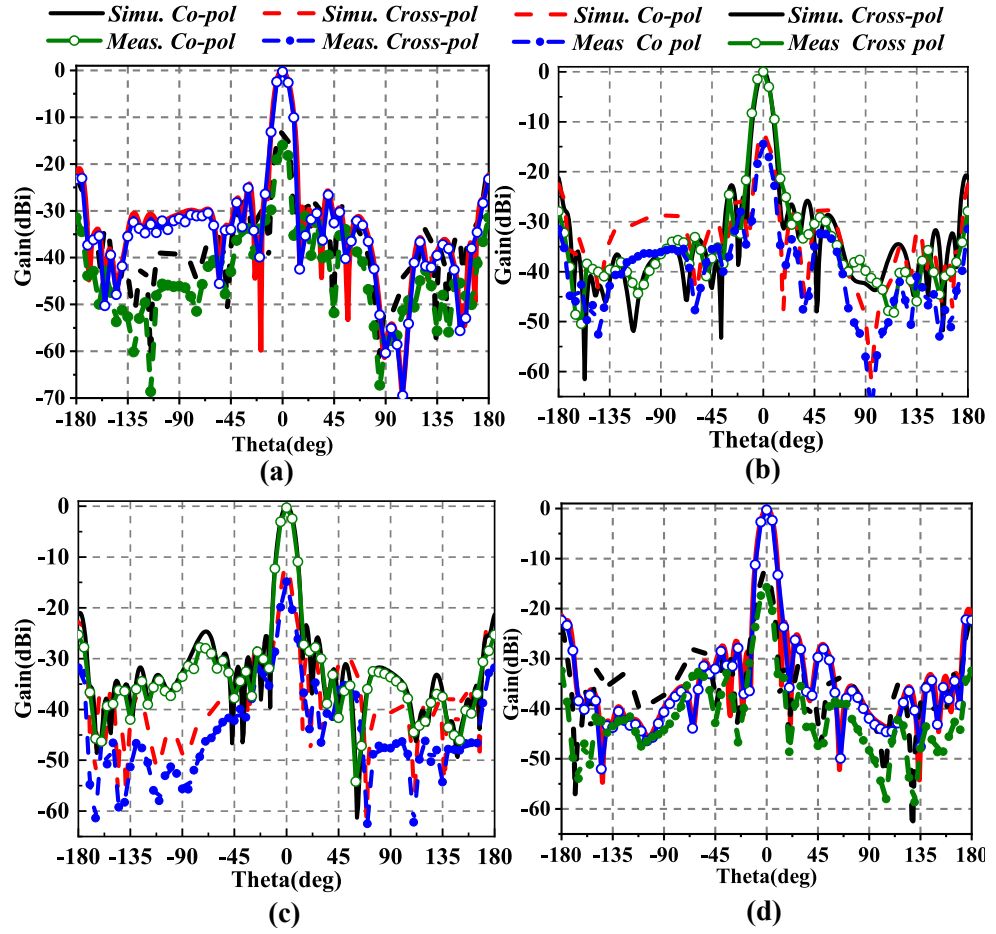


Figure 4.33: Radiation pattern in (a)-(b) at 26 GHz and (c)-(d) at 29 GHz in E-plane ($\phi = 45^\circ$) and H-plane ($\phi = 135^\circ$) respectively for ON state (CTRL = 3.3 V) of the proposed dual polarized array.

shown in Fig. 4.30. The proposed array achieves wide -10 dB impedance bandwidth in the desired frequency range from 24 - 32 GHz in both polarization states. The peak gain of the antenna array is 16.5 dBi with a stable average gain of 15.5 ± 1 dBi in the operating bandwidth. The radiation pattern of the proposed triangular antenna is plotted at 28 GHz in Fig. 4.31. The bottom ground layer of the SICL feed behaves as a good reflector and reflects the back radiation in the broadside direction. This results in radiation pattern with improved gain and Front-to-Back ratio (FTBR). The measured gain of the proposed single antenna is 5.7 dBi with cross-polarization level below 14 dB and FTBR of 21 dB. The radiation pattern of the array is plotted in Fig. 4.32 at 26/ 29 GHz in both E/H-plane with OFF state (CTRL = 0 V). Fig. 4.33 shows radiation pattern at 26/ 29 GHz for ON state (CTRL = 3.3 V). The antenna array maintains low sidelobe level of 26 dB in all states. The antenna array maintains an efficiency better than 91% in the desired operating frequency.

4.4.3 SICL Switching Board based Dual Beam Pattern Reconfigurable Antenna Array for Endfire Application

This study introduces a dual beam pattern reconfigurable antenna array designed specifically for 5G FR2 millimeter wave frequencies. Slanted $\pm 45^\circ$ dipole antennas are placed on the top substrate and are fed by the top and middle layer of the SICL feed section. Slanted configurations is utilized to make the array design compact to make the array suitable for dense 5G deployment. Further, the dipole ends are modified to reduce mutual coupling between the adjacently placed dipole arms in the array design. This results in better cross-polarization ratio. The proposed

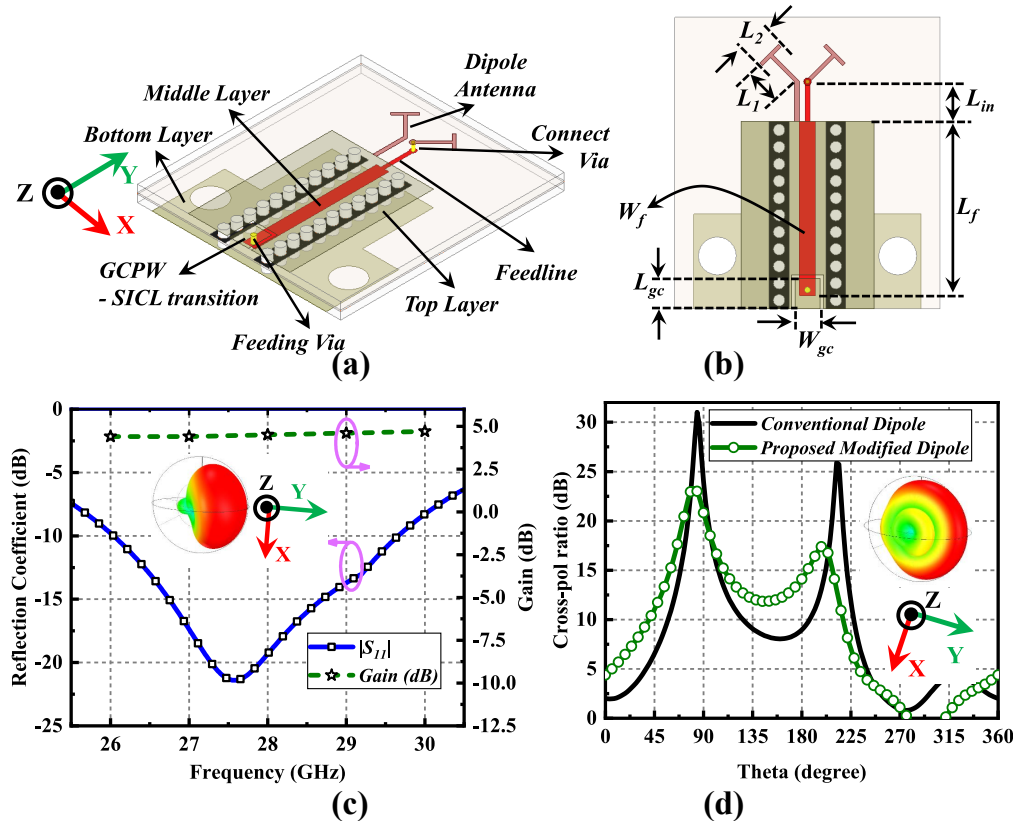


Figure 4.34: (a) Design of the proposed SICL fed modified dipole patch antenna and (b) its dimensions. (c) S-parameter and gain performance of the proposed modified dipole antenna. (d) Cross-pol ratio comparison of the conventional and proposed modified dipole antenna. The dimensions are (in mm) : $L_1 = 2$, $L_2 = 1.4$, $L_f = 9$, $L_{gc} = 1.7$, $W_{gc} = 1.45$, $W_f = 0.85$

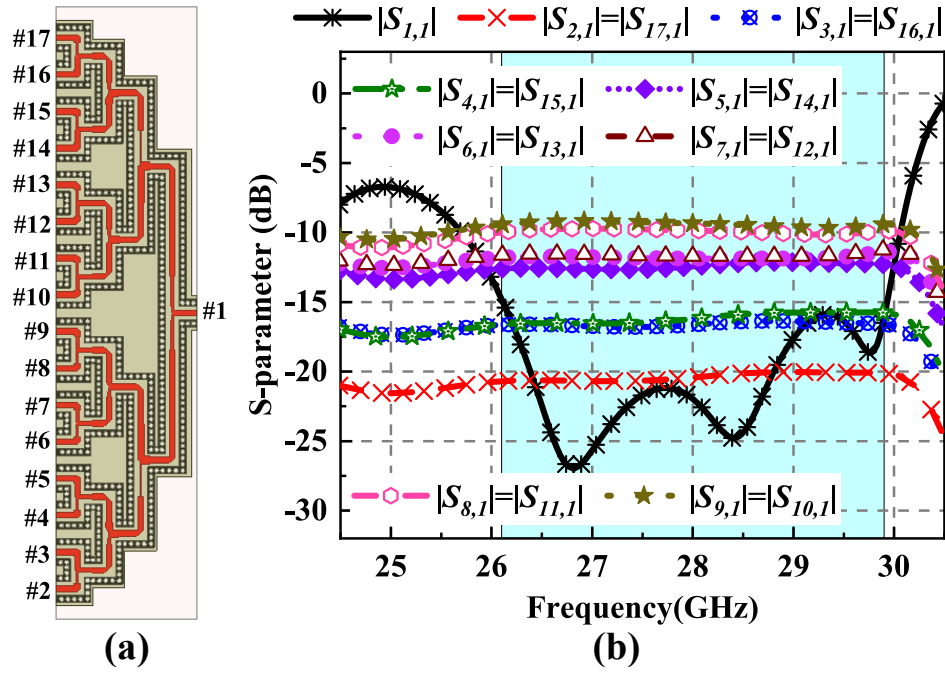


Figure 4.35: (a) Design, and (b) S-parameter plot of the proposed SICL based Taylor power divider feed network.

modified dipole antenna operates with a almost stable gain of 4.5 dBi over the wide operating bandwidth of 3.5 GHz for n257 FR2 mm-wave band. To achieve pattern reconfigurability, the SICL based novel switching board utilizing a low loss SPDT RF switch is introduced. Dual beam pattern reconfigurability is attained by the utilization of digital control on the SICL based switching board to stimulate two alternate antenna arrays at distinct time intervals. This system utilizes Half Duplex communication employing the Time Division Duplex (TDD) technique, which is one of the standard method for operating at 5G FR2 frequencies. The proposed antenna array provides wide bandwidth of 28.57 % at 28 GHz with an average stable gain of 13.5 dBi.

4.4.3.1 Design and Working Principle

A. Development of Broadband Modified Dipole Antenna

The design of the proposed modified dipole antenna is shown in Fig. 4.34. Unlike, the conventional dipole antenna having the two arms of the dipole placed linearly, the modified dipole antenna is designed by placing the two dipole arms orthogonally by having $\pm 45^\circ$ slant arrangement. One of the arm is fed by the top layer of the SICL feed network, while other arm is fed by the middle layer of the SICL line using a small *ConnectVia* as shown in Fig. 4.34(a). 50 Ω GCPW-to-SICL transition is used to excite TEM wave in the SICL feed section. The design dimensions are shown in Fig. 4.34(b). The performance of the proposed modified dipole antenna is shown in Fig. 4.34(c). The proposed antenna exhibits almost stable gain of 4.5 dBi with a wideband performance from 26 GHz to 29.8 GHz to support operation in the FR2 n257 band. The presented modified dipole antenna achieves an advantage of compact spacing to implement a linear array. A 1 x 4 linear modified dipole antenna array radiates endfire beam with high polarization purity in the forward direction ($0^\circ < \theta < 180^\circ$) as shown by the black curve in Fig. 4.34(d). To improve the polarization purity of the array, the ends of the dipole are further modified that reduces the orthognal cross-polarization component interfering with the radiation of the adjacent dipole arm. Thereby better polarization purity is achieved using the proposed modified dipole antenna as depicted by the green curve in Fig. 4.34(d). Thus, the final design of the modified dipole antenna consists of slanted $\pm 45^\circ$ dipole

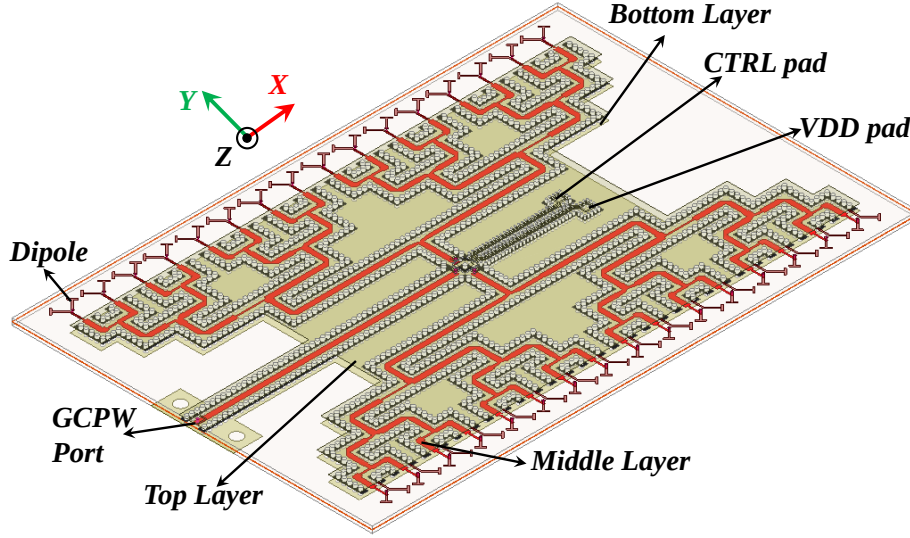


Figure 4.36: Design of the proposed SICL based pattern reconfigurable dual beam endfire antenna array.

arms with modified ends.

B. Design of SICL Low Sidelobe Taylor based Feed Network

To achieve high gain for mm-wave frequencies, a 1×16 linear array of proposed triangular patch antenna is designed. Taylor distribution based 1:16 SICL power divider is designed as shown in Fig. 4.35 to achieve 30 dB sidelobe level. The designed feed network obtains wide impedance bandwidth ($|S_{11}| < -15$ dB) with nearly $\pm 5^\circ$ phase difference between the output ports throughout the bandwidth.

C. Development of SICL based Pattern Reconfigurable Antenna Array

A pair of 1×16 linear array using modified dipole fed by SICL based Taylor power divider is

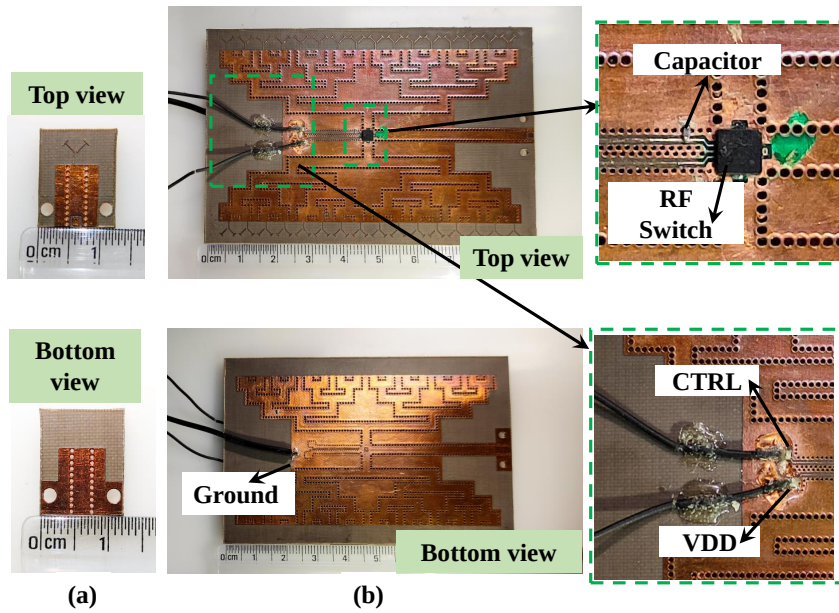


Figure 4.37: Fabricated prototype of the (a) single modified dipole antenna element and (b) proposed SICL based pattern reconfigurable dual beam endfire antenna array.

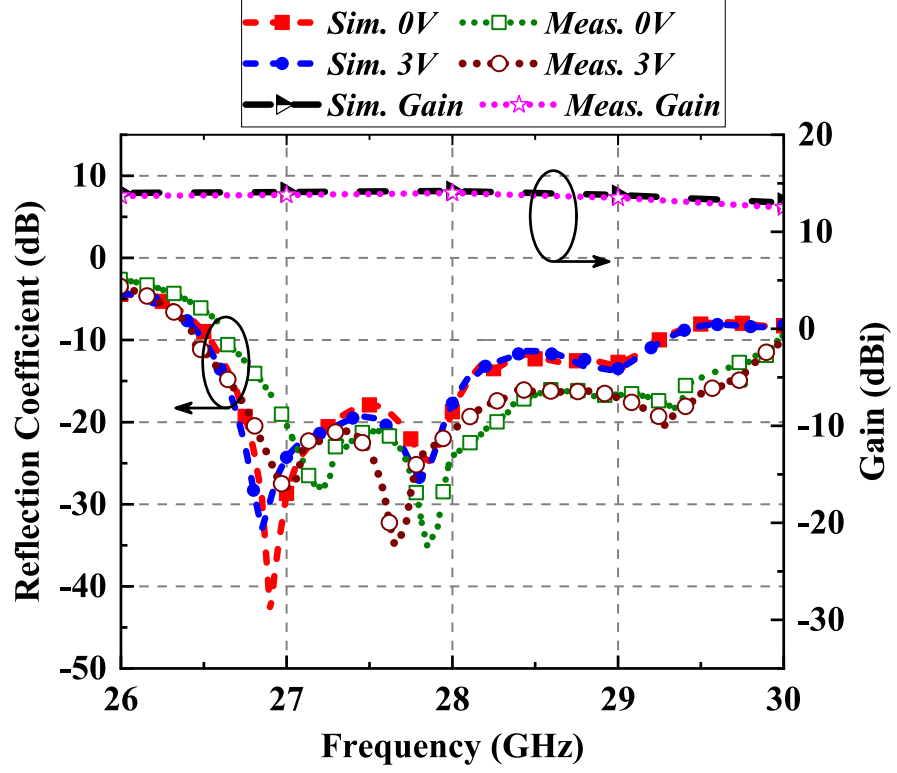


Figure 4.38: Reflection coefficient and Gain plot for the proposed SICL fed pattern reconfigurable dual beam antenna array.

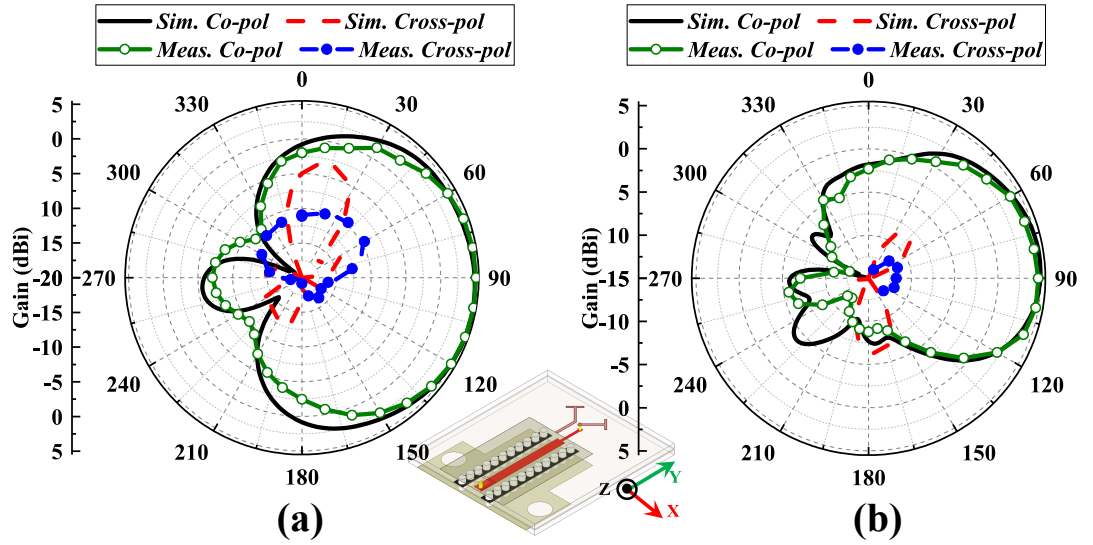


Figure 4.39: Radiation pattern at 28 GHz in (a) H-plane ($\phi = 90^\circ$) and (b) E-plane ($\theta = 90^\circ$) respectively for proposed SICL fed slanted modified dipole antenna.

designed as shown in Fig. 4.36 for achieving dual beam pattern with high polarization purity. Pattern reconfigurability is ensured in the antenna arrays by connecting it to the output RF lines (RF1, RF2) of the SICL based switching board as shown in Fig. 4.36. The orientation of the two antenna arrays fed by RF lines (RF1, RF2) as shown in Fig. 4.36 is chosen to attain bi-directional endfire pattern in the radiated beams.

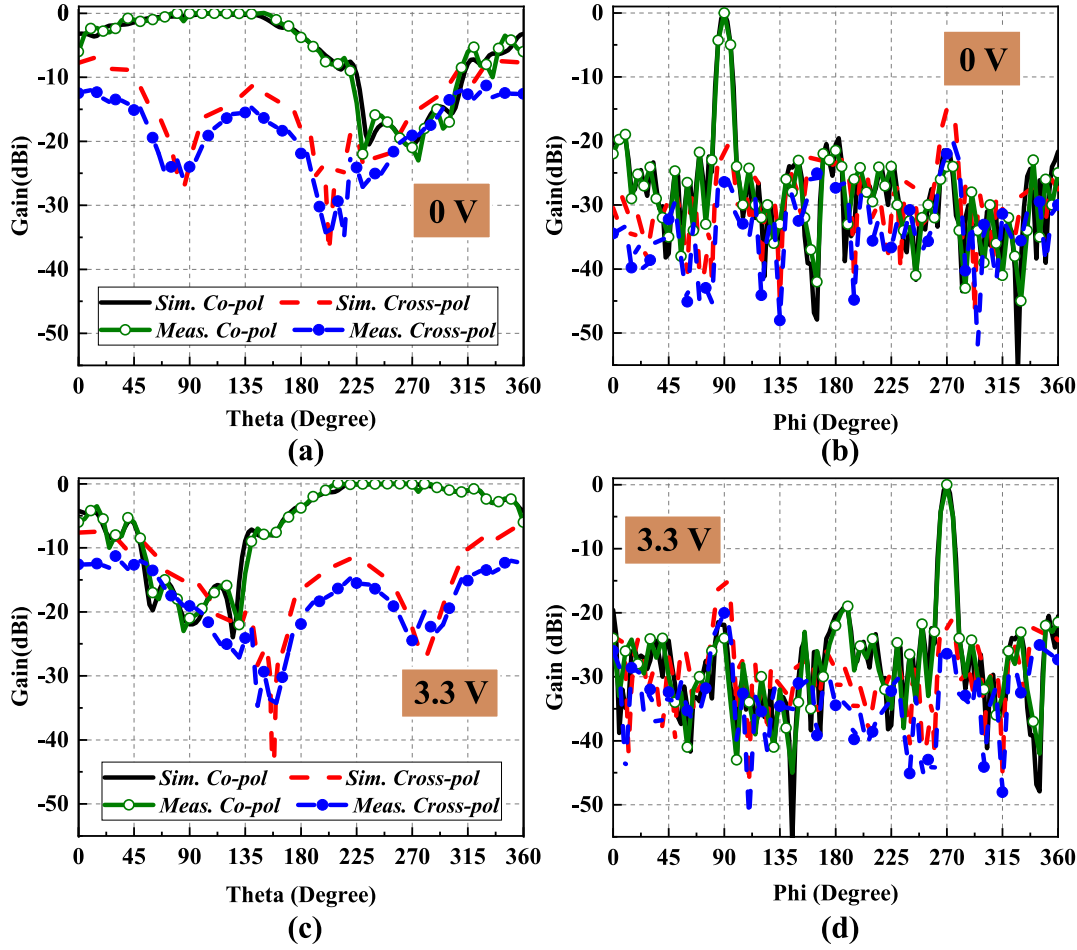


Figure 4.40: Radiation pattern in (a)-(b) for OFF state (CTRL = 0 V) and (c)-(d) for ON state (CTRL = 3.3 V) at center frequency 28 GHz in H-plane ($\phi = 90^\circ$) and E-plane ($\theta = 90^\circ$) respectively of the proposed pattern reconfigurable dual beam antenna array.

4.4.3.2 Results and Discussion

The fabricated prototype of the proposed SICL fed modified dipole antenna and pattern reconfigurable antenna array is shown in Fig. 4.37. Two connecting wires in the top view of the array in Fig. 4.37(b) are control (CTRL) and DC supply (VDD), while the bottom view shows the ground (black) for biasing the antenna array. The simulated and measured reflection coefficient of the proposed SICL fed modified dipole antenna array is shown in Fig. 4.38. The proposed array achieves wide -10 dB impedance bandwidth in the desired frequency range from 26.5 - 30 GHz in both polarization states. The peak gain of the antenna array is 14.0 dBi with a stable average gain of 13.5 ± 0.5 dBi in the operating bandwidth. The radiation pattern of the proposed modified slanted dipole antenna is plotted at 28 GHz in Fig. 4.39. The bottom ground layer of the SICL feed behaves as a good reflector and reflects the back radiation in the broadside direction. This results in radiation pattern with improved gain and Front-to-Back ratio (FTBR). The measured gain of the proposed single antenna is 5.2 dBi with cross-polarization level below 14 dB and FTBR 21 dB. Fig. 4.40 shows radiation pattern at 28 GHz for OFF state (CTRL = 0 V) and ON state (CTRL = 3.3 V) of the proposed pattern configurable dual beam antenna array. The antenna array maintains low sidelobe level of 26 dB in all states with low cross-polarization ratio of 27 dB.

SICL based switching board utilizing low loss RF SPDT switch for mm-wave digital control is presented here. This work shows easy integration of SMD components over SICL transmission line with demonstration in 5G mm-wave frequencies.

4.5 HMSICL fed Stacked Monopole Antenna Array

This Section presents a novel half mode antenna designed using the Substrate Integrated Coaxial Line (SICL) technology for endfire applications. In order to reduce the size of the antenna designs for dense 5G deployments, a study on antenna array using half the size of SICL cavity to feed antenna is presented here.

A 28 GHz SICL cavity is bisected along its plane of symmetry (PMC) to form an open-ended half mode SICL cavity. The HMSICL cavity is fed by SICL feed line to form half mode SICL (HMSICL) antenna. The half mode cavity dimensions are optimized to have sufficient gain at 28 GHz. To increase bandwidth, the middle layer of the cavity is tapered exponentially towards the endfire direction. This results in bandwidth increment to 500 MHz. Further, slots are etched on the top and bottom plate of the HMSICL cavity to result in bandwidth of 1.2 GHz. Two such HMSICL fed antennas are designed at 27.5 GHz and 28.5 GHz which are further stacked to exhibit bandwidth of 2.7 GHz for its potential application focused for n257 band.

Novel feeding techniques are employed to have a broadband multilayer SICL feeding network to support the bandwidth requirement of the proposed antenna array. Subsequently to validate the antenna performance for practical mm-wave applications, a linear array of HMSICL antennas is presented. In the array, Dolph-Tschebyscheff feeding network with -25 dB sidelobe level is utilized to attain low sidelobe radiation pattern.

4.5.1 Design

The technique to obtain antenna array for broadband application is presented in Fig. 4.41. The basic design of the HMSICL cavity fed monopole antenna is presented in Section 3.6. Following the same design principles, a HMSICL cavity fed monopole antenna design is developed for 27.5 GHz as shown by *CaseA* in Fig. 4.41(a). As discussed earlier, the proposed antenna exhibits a bandwidth of 500 MHz. To further increase the bandwidth, slots are etched on the top and bottom plate of the HMSICL cavity to result in *CaseB* antenna design which resonates at 28.5 GHz with a bandwidth of 1.2 GHz. A multi-layered antenna array design of *CaseB* antenna are stacked and fed by a common GCPW port to result in the *Stacked Array* design as shown in Fig. 4.41(c). The gradual increase in the bandwidth of the proposed multilayer HMSICL cavity stacked antenna array is depicted in Fig. 4.41(d).

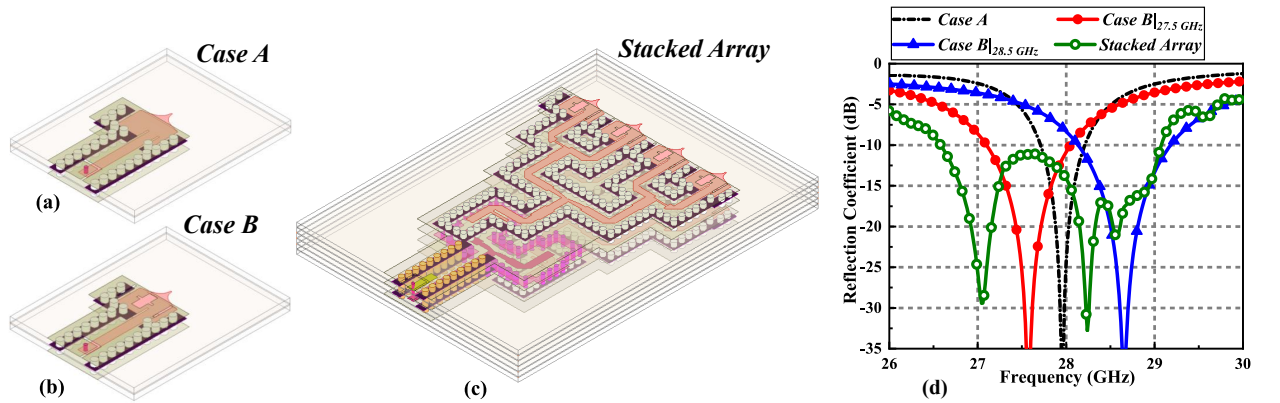


Figure 4.41: Evolution of the proposed novel multilayer stacked HMSICL cavity fed antenna array design. Isometric view of (a) HMSICL cavity fed antenna (*CaseA*), proposed slotted HMSICL cavity fed antenna (*CaseB*) and (c) multilayer stacked HMSICL cavity antenna array. (d) Performance evaluation in terms of bandwidth comparison of the proposed antenna array design.

4.5.1.1 Proposed Slotted HMSICL Cavity fed Antenna

The design of the proposed slotted HMSICL cavity fed monopole antenna is shown in Fig. 4.42. The design dimensions are presented in Fig. 4.42(b) and layerwise configuration depicting the top, middle and bottom layers of the antenna is presented in Fig. 4.42(c). Two longitudinal slot and a cross slot is etched in the top and bottom layers of the HMSICL cavity to have better bandwidth performance. A 50 Ω Grounded Co-Planar Waveguide (GCPW) to SICL transition is used to feed the antenna using a small feeding via. The width of the feed line W_f is chosen for 50 Ω characteristic impedance of the feed line.

The proposed HMSICL cavity stacked antenna array is based on stacking of two HMSICL cavity fed antennas operating at 27.5 GHz and 28.5 GHz. The challenge comes in designing a common feed to excite the two antennas operating at distinct frequencies. When such a design is fed by a single transmission line, there occurs reflections that affects the operation of the other antenna. Hence, a novel feeding network has to be design with utmost care to enable simultaneous operation for the two stacked antennas. In the next section, the step-by-step design procedure to

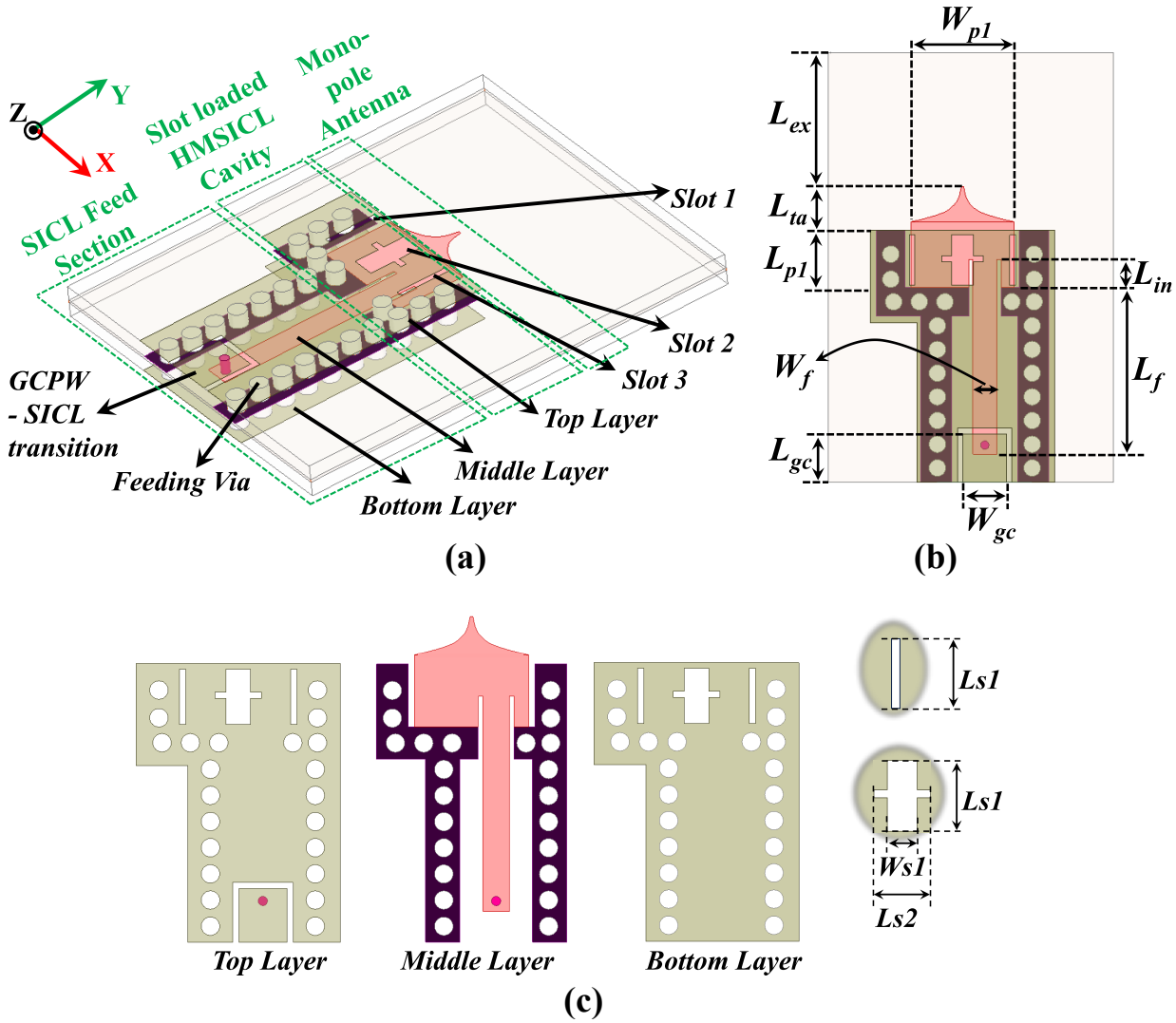


Figure 4.42: Geometry of the proposed Half Mode SICL cavity fed monopole antenna in (a) isometric view, (b) top view and (c) layerwise configuration.

The dimensions are (in mm) : $L_{ex} = 4.3$, $L_{ta} = 1.25$, $L_{p1} = 2.55$, $W_f = 0.85$, $L_{gc} = 1.7$, $W_{gc} = 1.54$, $L_f = 6$, $L_{in} = 1$, $L_m = 0.3$, $W_{p1} = 3.7$

have a novel multilayer SICL feeding network to have broadband performance is discussed.

4.5.1.2 Design of Novel Multilayer GCPW-to-SICL Transition

The geometry of the novel multilayer GCPW-to-SICL transition is shown in Fig. 4.43. The position of the proposed transition in the feed network of the HMSICL stacked antenna array along with its enlarged view is shown in Fig. 4.43(a)-(b). Two SICL structures are stacked together with *Layer1* - *Layer3* being the top SICL transmission line and *Layer3* - *Layer5* forming the bottom SICL transmission line structure. *Layer3* is common ground plane for both the SICL lines. Next, a *Feedingvia* connecting the signal line of the Grounded Co-Planar Waveguide (GCPW) to the middle layer of the bottom SICL line *Layer4* is used to excite the TEM wave in the multilayer SICL structure as shown in Fig. 4.43(c). To have proper impedance match, a GCPW cut is made in *Layer3* and a small portion of middle *Layer2* of the top SICL is placed. The proposed multilayer GCPW-to-SICL transition obtains a wide bandwidth with low insertion loss (< 0.5) as shown in

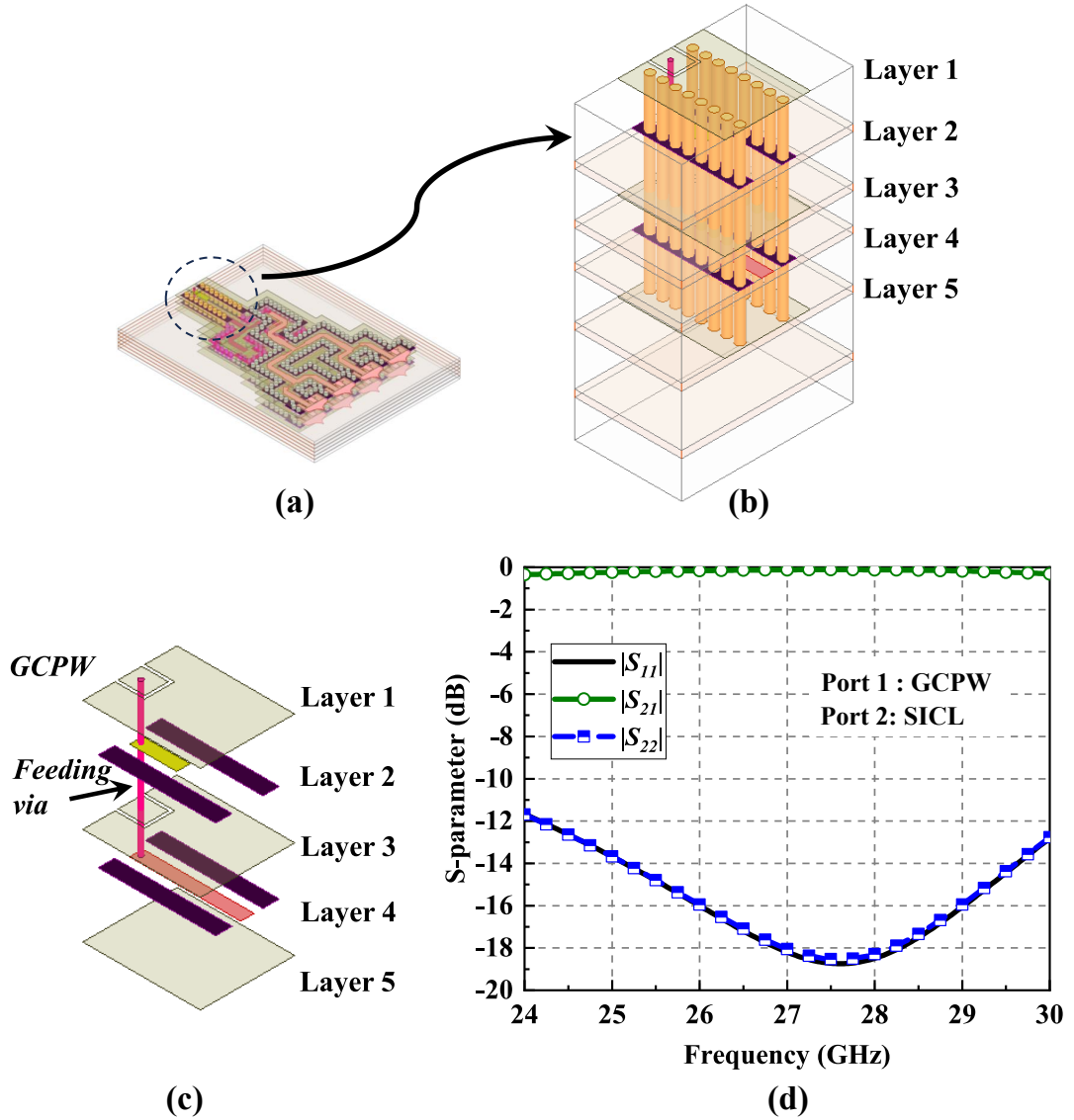


Figure 4.43: Geometry of novel multilayer GCPW-to-SICL transition. (a) Position of the proposed transition, (b) enlarged view and (c) layerwise exploded configuration. (d) S-parameter performance of the proposed transition.

Fig. 4.43(d).

4.5.1.3 Design of Novel Multilayer SICL Equal Power Divider

To feed the two stacked antennas, it is required to distribute the power uniformly in the two middle layers of the stacked SICL transmission line. In order to enable such a distribution, a third SICL layer is introduced as shown in Fig. 4.44 where *Layer6* acts as the middle layer and *Layer7* acts as the bottom layer with *Layer5* being common between the middle and bottom SICL stacked structure. 1:2 equal power divider is used in implemented in the middle layer (*Layer4*) of the middle SICL transmission line. Next, two half-wavelength ($\lambda_g/2$) C-shaped slots are etched in *Layer3* (bottom of the top SICL) and *Layer5* (top of the bottom SICL) to couple the power in the middle layers of the top and bottom SICL lines. The orientation of the slots are reversed in order to maintain the phase difference between the two output ports. The S-parameter performance of the designed novel multilayer SICL equal power divider is shown in Fig. 4.44(d) that depicts its wideband operation from 26.5 GHz to 31 GHz where the phase difference between the output ports

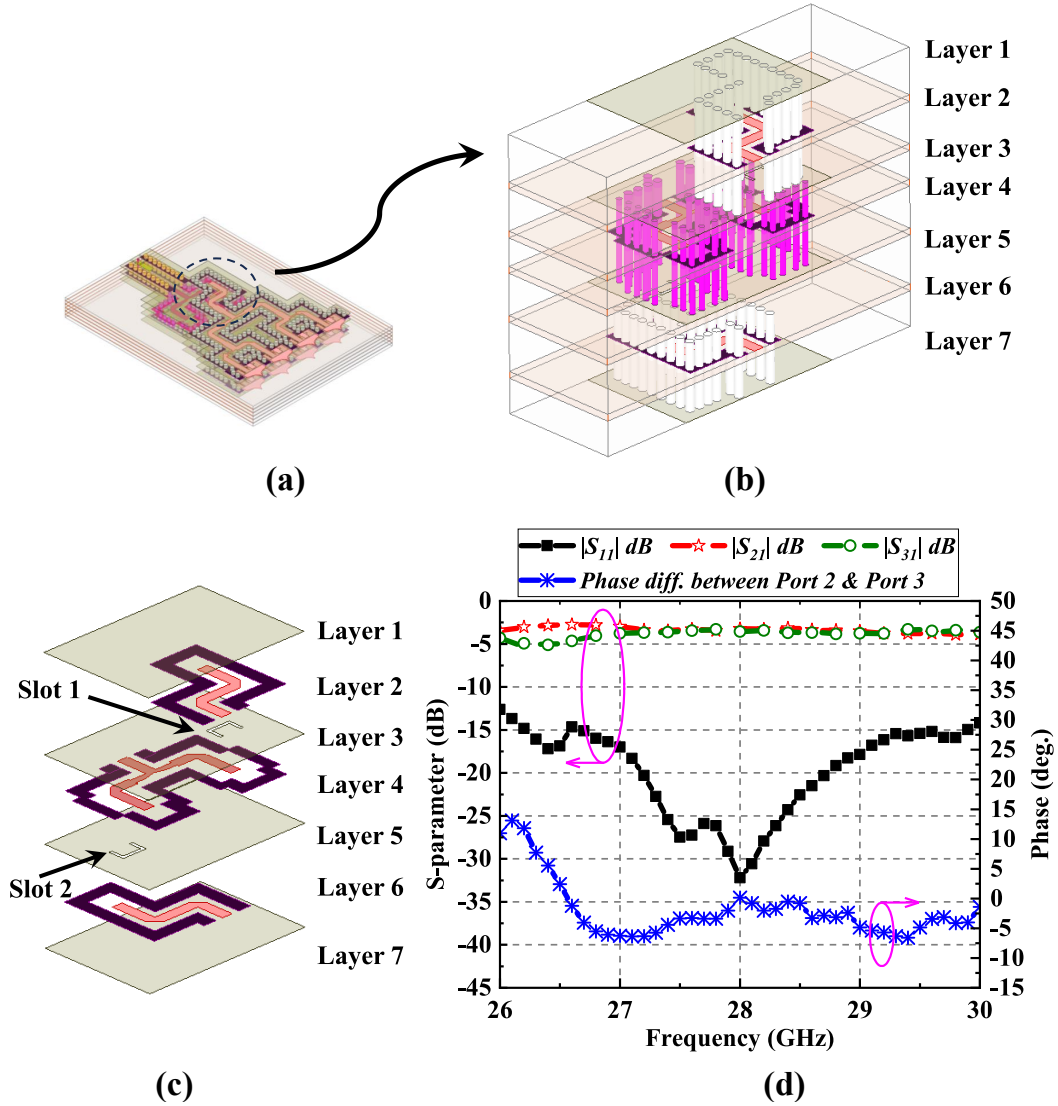


Figure 4.44: Geometry of novel multilayer SICL equal power divider. (a) Position of the proposed power divider, (b) enlarged view and (c) layerwise exploded configuration. (d) S-parameter performance of the proposed power divider.

is in the range $\pm 5^\circ$ and reflection coefficient is below -15 dB.

4.5.1.4 Design of Linear 1×4 Dolph-Tschebyscheff Power Divider

To look into the practical validation of the proposed HMSICL cavity antenna, the goal is to synthesize a four element equispaced linear array to achieve high gain with suppressed sidelobes. A 1×4 HMSICL cavity antenna array with Dolph Tschebyscheff corporate feed network is chosen with desired -25 dB sidelobe level. The excitation amplitude ratio to achieve -25 dB sidelobe level are: $I_{-2} : I_{-1} : I_1 : I_2 = 0.459 : 1 : 1 : 0.459$. The designed feed network consists of two stages to design a four way unequal power divider as shown in Fig. 4.45(b) and (c). The width of SICL line at input port and output port of the individual power divider stage is $W1$ (50Ω). *Stage1* is an equal power divider formed by T-junction with each arm of width $W2$ (70.7Ω). *Stage2* is formed by two T-junction power divider that divides the power unequally between the output ports. The widths $W4$, $Wj2$ and $W3$ are chosen carefully to have desired output power levels. To match output with 50Ω , odd multiple of quarter wavelength $(2(n+1)\lambda_g/4)$ section at 28 GHz is used. The dimensions of the feed network is given in Fig. 4.45.

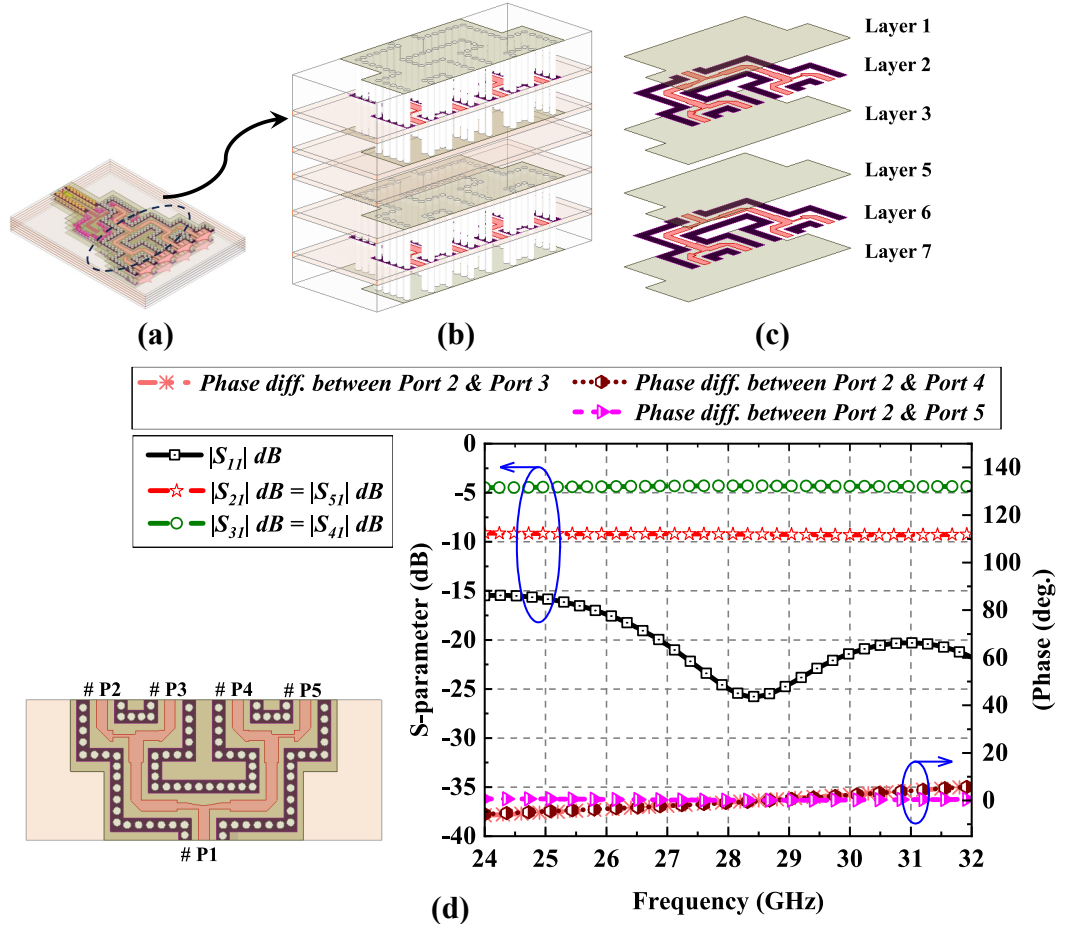


Figure 4.45: Design of the proposed SICL Dolph-Tschebyscheff power divider in (a) position of the proposed power divider, (b) enlarged view and (c) layerwise exploded configuration. (d) Performance of the designed SICL Dolph-Tschebyscheff power divider.

The dimensions are (in mm) : $W1 = 0.85$, $W2 = 0.5$, $W4 = 1.0$, $Wj2 = 1.23$, $W3 = 0.23$.

4.5.1.5 Design of Proposed Multilayer HMSICL cavity fed Antenna Array

The design of the proposed multilayer HMSICL cavity fed antenna array is shown in Fig. 4.46. *Layer1 - Layer3* forms the top HMSICL cavity fed monopole antenna array that operates at 27.5 GHz. While *Layer5 - Layer7* forms the top HMSICL cavity fed monopole antenna array that operates at 28.5 GHz as shown in Fig. 4.46(a). Layerwise feeding network and its exploded view is shown in depicted in Fig. 4.46(b), where *Layer3 - Layer5* forms the middle SICL transmission line. When the stacked antenna array is fed by the proposed feed network, the antennas are not properly excited. This occurs due to the change in the input impedance from the loading of the antenna array, as seen from the feed at C-shaped slot coupling. Hence it is required to compensate the loading effect from the array. Quarter-wave transformers (QT/f1, QT/f2) to match the real impedance and stubs (Stub1, Stub2, Stub3) to match the imaginary part of the impedance are added in the respective feed layers of the antenna array in *Layer2* and *Layer6*. Fig. 4.46(c) shows the middle layers of the proposed feed network in the top and bottom SICL line. The final design of the array is shown in Fig. 4.46(d). The effects of the matching network is shown in Fig. 4.47.

4.5.2 Results and Discussion

The experimental results along with the fabricated prototype is shown in Fig. 4.47. The measurement of the fabricated antenna is performed using PNA-L Network Analyzer (model no. N5234A). To facilitate connection of the antenna with the coaxial cables, Rosenberger coaxial connector (09K243-40ME3) is used. The simulated and measured resonant frequency of the proposed 1 x 4 HMSICL antenna array is 28 GHz as shown in Fig. 4.47. The measured bandwidth of the array is 2.7 GHz (26.5 GHz to 29.2 GHz). A small deviation in reflection coefficient occurred due to the tolerance in fabrication setup. The fabricated prototype of the array is shown in Fig. 4.48(b) and (c). The simulated and measured radiation pattern of the proposed HMSICL antenna is shown in both E and H plane in Fig. 4.49. Due to the HMSICL cavity acting as the reflector for

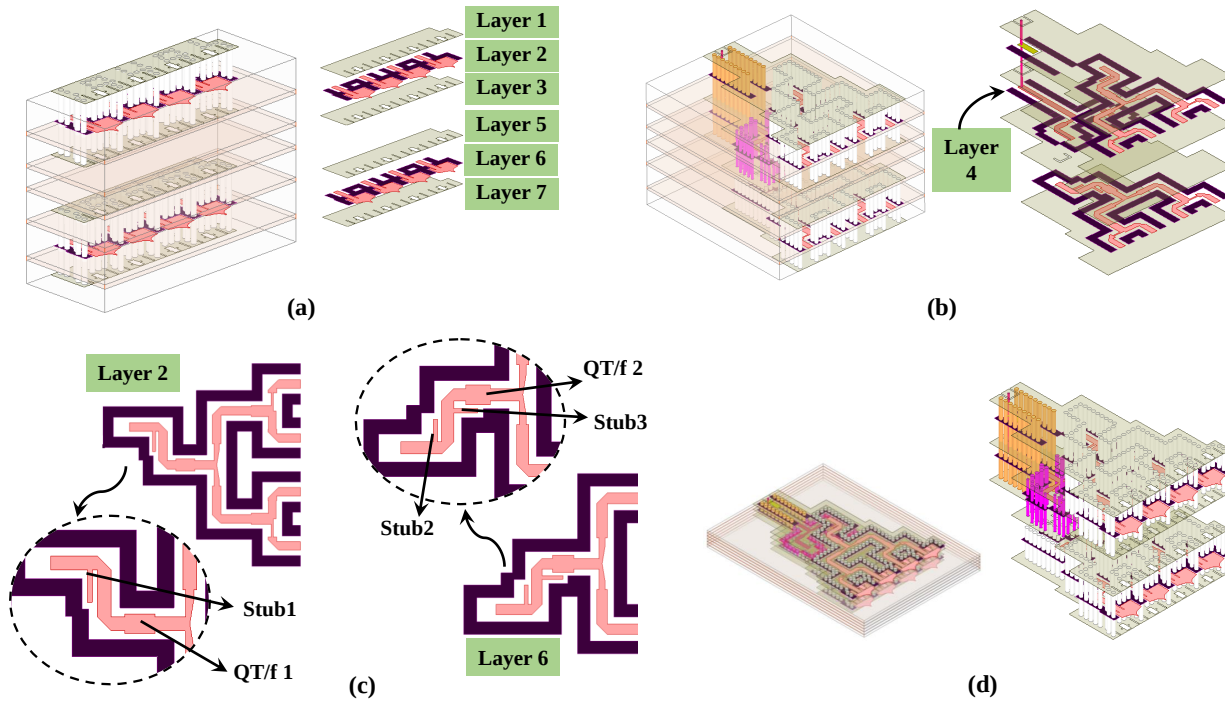


Figure 4.46: Geometry of the proposed HMSICL cavity fed monopole antenna array. (a) HMSICL cavity fed antenna array, (b) SICL based multilayer feed network. (c) Layers of the modified SICL feeding the antenna array. (d) Final design of the proposed multilayer HMSICL stacked antenna array.

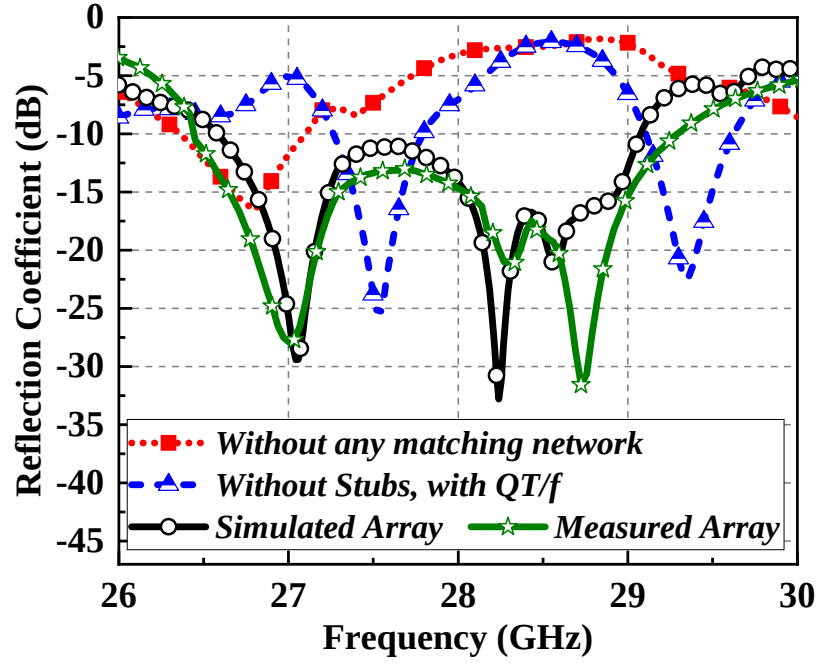


Figure 4.47: Reflection coefficient of the proposed multilayer stacked HMSICL antenna array.

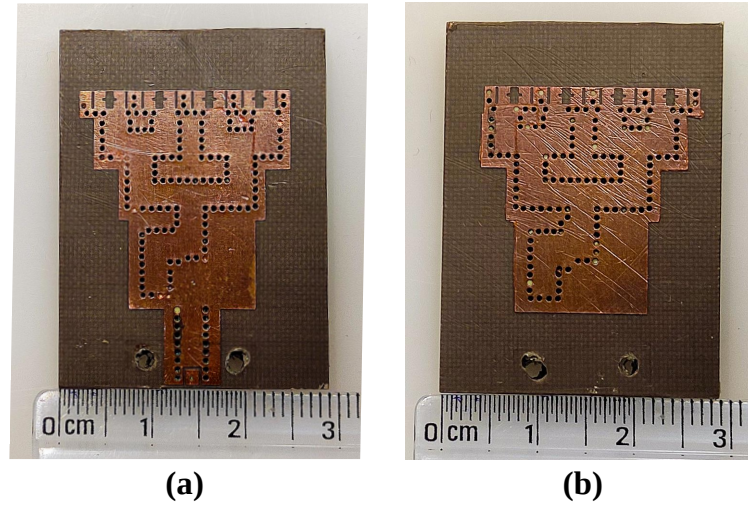


Figure 4.48: (a) Top view and (b) bottom view of the proposed multilayer stacked HMSICL antenna array.

the back radiations, the back lobe is suppressed and thereby antenna achieves a front-to-back ratio (FTBR) of 31.1 dB along with good polarization purity (Co-to-Cross pol ratio = 16.8 dB). The measured gain of the antenna is 6 dBi which is close to the simulated gain of 6.4 dBi. Deviation in the measured gain occurs due to the tolerance in the measurement setup. The measured radiation pattern of the array aligns well with the simulated pattern as shown in Fig. 4.50. The simulated gain of the array is 11.5 dBi and measured gain of the array is 11.1 dBi with measured sidelobe level of 24.2 dB. The FTBR of the array is 26.6 dB and co-pol to cross-pol ratio is 29.2 dB. The half power beamwidth (HPBW) of the proposed array is 27°. The difficulty faced in the presented work is mainly dependent on the fabrication and measurement setup. The antenna elements in the array is found to be susceptible to frequency shift due to the via-hole fabrication aberrations. Due

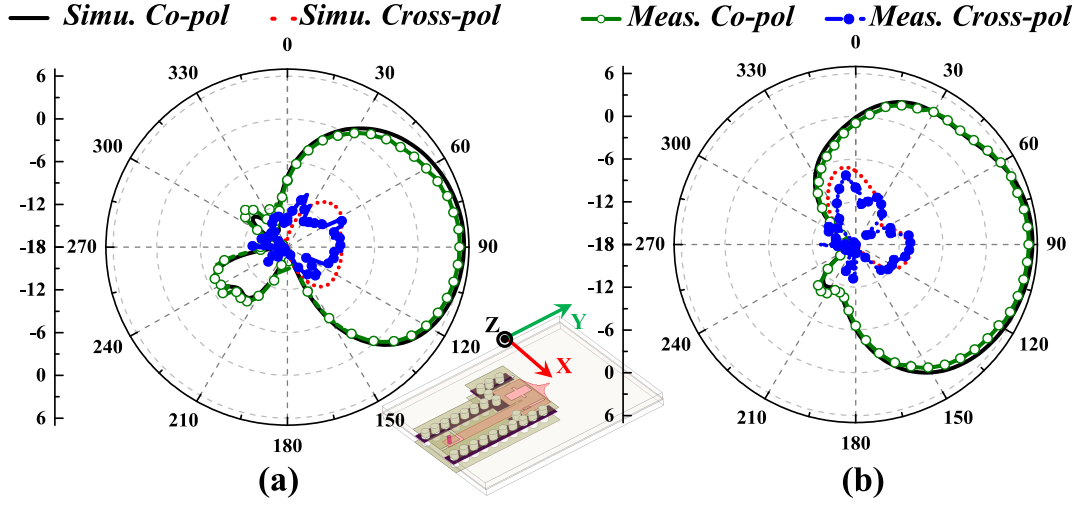


Figure 4.49: Radiation pattern in (a) H-plane ($\theta = 90^\circ$), (b) E-plane ($\phi = 90^\circ$) of the proposed single HMSICL antenna at the center frequency.

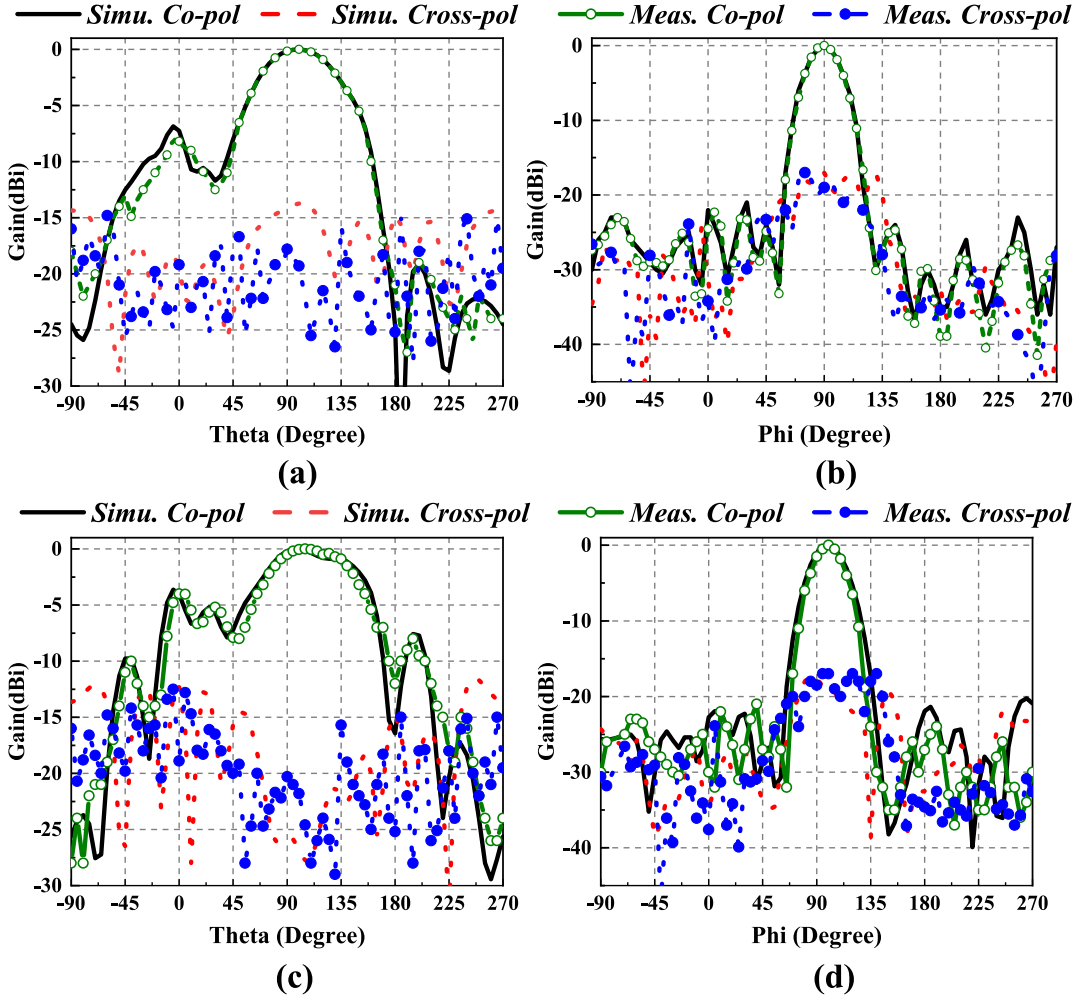


Figure 4.50: Radiation pattern in (a) H-plane ($\theta = 90^\circ$), (b) E-plane ($\phi = 90^\circ$) of the proposed multilayer stacked HMSICL antenna array at the center frequency.

to the inclusion of blind feeding via for feed, vertical misalignment between the prepreg may lead to losing conductivity. Hence, fabrication of the designed prototype must be carried out with utmost care.

The proposed HMSICL stacked antenna array exhibits a gain of 11.5 dBi and 500 MHz bandwidth with low cross polarization level below 35.8 dB. Measured results of the proposed antenna array matches well with the simulated results and thereby encourages its deployment in the 5G application. The presented work is a novel endfire Half Mode SICL cavity based design with much smaller footprint suitable for numerous 5G user equipment applications like handheld device and personal digital assistants (PDAs) services for 5G.

4.6 Conclusion

In this chapter, design principles for high-gain antenna arrays for 5G mm wave applications have been studied. The slot antennas useful for flush mounted applications have been utilized to design slot antenna arrays. 2 x 4 C-shaped slot antenna array is proposed for unidirectional radiation characteristics with slots etched in the top plate of the SICL feed section. 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. These arrays are useful in applications requiring smaller footprint. However, the bandwidth with slot antenna arrays is narrow. In order to increase the bandwidth, compact linear arrangement of dipole antenna configurations in a small footprint have been studied. To improve bandwidth while maintaining a compactness for array design, a novel technique to implement crossed dipole antenna in SICL technology is proposed that exhibits wideband performance. The two layers (top and middle) are utilised to feed the slanted dipole arms in a stacked geometry that gives compactness to the array design.

To explore reconfigurability in antenna array designs, novel on-board integration is explored that eliminates the complexity of having different RF chain assemblies between antenna array and controlling (switching) board. 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. These works bring about the advantage of SICL over its counterpart by supporting IC mounting over the SICL transmission line. Further, stacked configuration of the HMSICL antenna is utilized to improve the bandwidth of the proposed HMSICL array. It requires a feed network with impedance matching at each step of the design. Novel feed configuration with multilayer GCPW-to-SICL transition, multilayer slot-coupled equal power divider, impedance matching network has been presented with three SICL stacked configuration with common ground layers. This design produces wide bandwidth to support n257 band of the 5G FR2 mm wave band.

