

Substrate Integrated Coaxial Line fed Dipole Antenna Element Designs

2.1 Introduction

In this chapter we will see the advantage of Substrate Integrated Coaxial Line (SICL) as a simplest and compact feeding technology for the planar antennas, in particular dipole antennas. Further we shall see the techniques to incorporate two functionalities, namely wide bandwidth and dual polarization in dipole antennas using SICL feed, which thereby appreciates the effectiveness of SICL in achieving these performances.

In general, the basic configuration of dipole antenna gives narrow bandwidth. For practical applicability at 5G FR2 band, the bandwidth of the antennas need to be enhanced. This chapter covers few dipole antenna configurations to achieve enhancement in bandwidth. The design aspect, operating principle and performance of these antennas is presented in detail. The concept of polarization diversity offers potential for simultaneous transmission and reception of radio frequency signals in two orthogonal polarizations i.e. both horizontal and vertical polarization. It avoids multipath fading losses and enhances channel capacity of the wireless systems. Major advantages associated with polarization diversity are: *increased capacity* (approximately doubles channel capacity compared to single polarization), *enhanced data rates* (two orthogonal polarizations allows for higher data rates), *improved reliability* (maintains steady communication as a backup polarization when one polarization is affected) and *effective utilization of spectrum* (more data transmission in the available bandwidth) in different communication scenarios.

Designing antennas at mm-wave frequencies adds even more challenges to it. *Isolation* between polarizations is the basic challenge when it comes to designing dual polarized antennas. Maintaining good isolation between horizontal and vertical polarization is crucial to prevent interference between two signals. High *cross-polarization discrimination* (ability of an antenna to transmit and receive signals in only one polarization while rejecting signals in the orthogonal polarization) calls for strategic development of these antennas. MM-wave spectrum adds another level of complexity to dual polarized antennas. The compact size and form factor of circuit design at mm-wave frequencies brings the antenna in close proximity, which results in interference and mutual coupling that degrades the isolation performance of the antennas. The compact and shielded nature of Substrate Integrated Coaxial Line (SICL) enables designing dual polarized antennas in small form factor while providing isolation from its inherent self-shielded structure.

The chapter ² is organized as follows. In Section 2.3, a broadband dipole antenna excited by SICL feed section is designed that uses stagger tuning from parasitic dipole to achieve improvement in bandwidth [Baghel and Mukherjee, 2018b]. In Section 2.4, we propose a Quasi-Yagi antenna fed by SICL feed section to improve the bandwidth and gain of a dipole antenna [Baghel and Mukherjee,

²This chapter is based on the publication [Baghel and Mukherjee, 2018b], [Baghel and Mukherjee, 2018c], [Baghel and Mukherjee, 2020b], [Baghel *et al.*, 2021; Baghel and Mukherjee, 2021c; Baghel *et al.*, 2023].

2018c]. We propose a conventional bow-tie antenna excited by SICL feed network, in Section 2.5 that attain wide bandwidth in the FR2 band centered at 28 GHz Baghel and Mukherjee [2020b]. Further, we shall explore few novel techniques in designing dipole antennas to exhibit dual polarized performance. Substrate Integrated Coaxial Line (SICL) based dual polarized antennas have been designed for low frequency that utilises SICL slot and printed patch/ monopole as the two radiating antenna elements to give orthogonal linear polarization [Gao and Song, 2019; Wang *et al.*, 2019]. Section 2.6 presents a novel, simple and compact SICL based dual polarized antenna for millimeter wave spectrum. The proposed dual polarized antenna operates at 28.1 GHz with wide impedance bandwidth (31%). Instead of using the traditional technique of placing two orthogonal antennas side by side, the presented work utilizes the multilayer structure of SICL by placing two orthogonal antennas ($+45^\circ$ and -45° inclined dipoles) on either sides of the substrates. This approach allows for minimizing the space requirement while maintaining gain and wide band performance. Section 2.7 presents a dual polarized dipole antenna that provides polarization diversity by selectively choosing the port excitations of the two side-by-side placed antennas. Further, an array of the proposed dual polarized dipole antenna is designed by stacking the proposed antenna along the broadside (z-axis) direction. The array produces endfire radiation with good front-to-back ratio (FTBR) and cross-polarization level of 12.13 dB and 22.39 dB respectively. The dual polarized array composed of orthogonally co-located dipole antennas produces orthogonal polarized beam polarization diversity application. Section 2.8 proposes a novel dual polarized SICL fed antenna. The uniqueness of the proposed design lies in compactness achieved by placing a dipole antenna and folded patch antenna in close proximity and feeding by a single SICL feed line. The presented antenna achieves a linearly polarized unidirectional broadside beam at first operating frequency 26.1 GHz and broadside LHCP beam at second operating frequency 28.95 GHz. Finally, we conclude the chapter in Section 2.9

2.2 Comparison of Substrate Integrated Coaxial Line (SICL) and Coplanar Stripline (CPS) technology

In this section, a comparative study is presented between Substrate Integrated Coaxial Line (SICL) and Coplanar Stripline (CPS) technology as feeding to antenna system. A dipole antenna is designed and fed by SICL and CPS as shown in Fig. 2.1.

- SICL fed dipole antenna: A middle conducting strip is enclosed between the top/bottom and via-wall in Substrate Integrated Coaxial Line (SICL) technology as shown in Fig. 2.1(a). The side via-wall provides lateral shielding to the middle strip and thus, the feed section remains unaffected from the surface waves.
- Coplanar stripline (CPS) fed dipole antenna: The co-planar strips are placed side-by-side and feed the two dipole arms as shown in Fig. 2.1(b). Hence, the strips of CPS feed are unshielded by the inherent nature of the CPS technology. This results in surface waves to propagate along the surface of the dielectric substrate in CPS fed dipole antenna.
- Surface waves comparison: The side via-wall provides lateral shielding to the middle strip and thus, the feed section remains unaffected from the surface waves. Fig. 2.2 depicts the wave propagation in the dipole design excited by SICL and CPS feed sections respectively. It is seen that the surface waves are not present in the SICL based design, while the surface waves are clearly seen to propagate along the dielectric substrate.
- Performance Comparison: The performance of the two antenna is shown in Fig. 2.3, 2.4 and 2.5. Fig. 2.3 shows the reflection coefficient of the dipole antenna excited by SICL and CPS. The green curve of the SICL fed dipole shows sharp resonance in comparison to the blue curve of the CPS fed dipole. This is due to the surface wave interactions with the feed section in

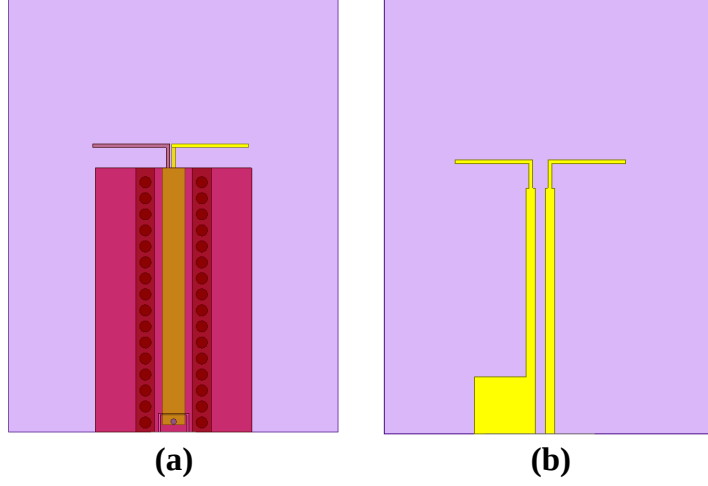


Figure 2.1: Design of (a) SICL and (b) CPS fed dipole antenna.

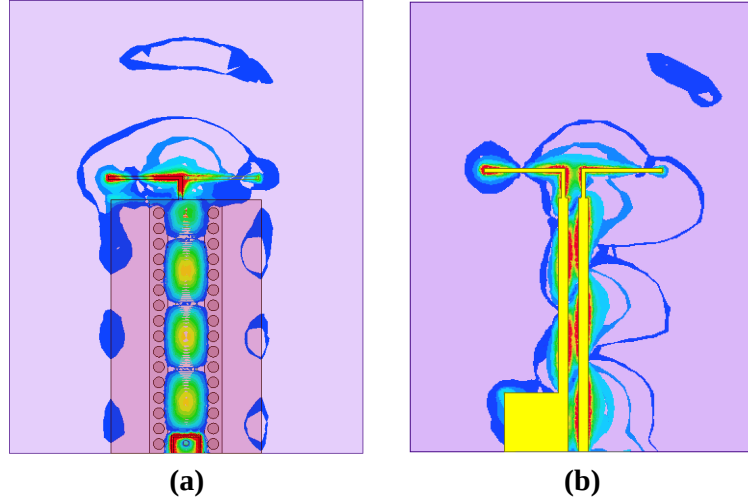


Figure 2.2: Magnitude of electric field distribution for (a) SICL and (b) CPS fed dipole antenna.

CPS that results in undesired modes. The gain comparison shown in Fig. 2.4 clearly shows that the dipole antenna achieves higher gain (7.7 dB) with SICL feed section.

- Fig. 2.5 shows radiation pattern of two antennas in the H-plane. Grating lobes is clearly visible in CPS fed dipole due to the unwanted radiations from surface wave.
- SICL fed dipole antenna achieves much higher cross-polarization ratio of 18 dB while CPS fed dipole antenna achieves lower cross-polarization ratio of 8 dB due to the surface wave generation in the CPS feed.
- Front-to-Back-Ratio (FTBR) of 16 dB is observed in SICL fed dipole while FTBR of 2.5 dB is observed in CPS fed dipole. This is due to the fact that the top and bottom ground plane of the SICL feed acts as reflector for the back radiation and thereby reduces the back lobe.

Thus, SICL technology serves as the optimum feeding network for designing mm-wave antenna designs.

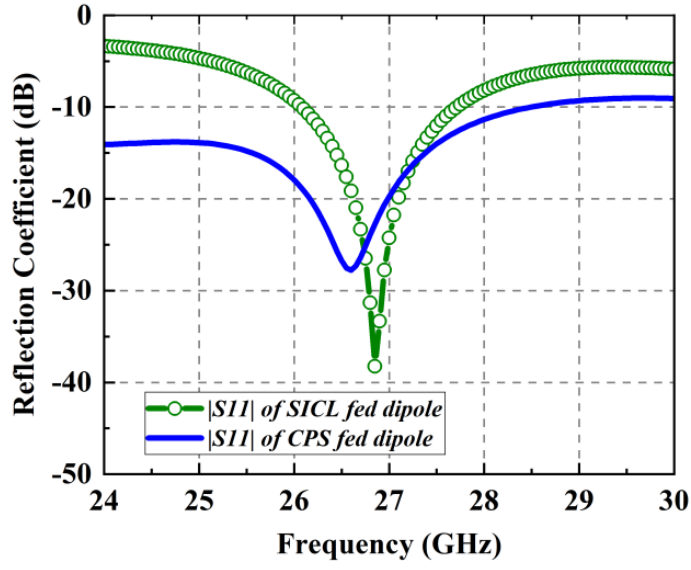


Figure 2.3: S-parameter plot of SICL and stripline fed dipole antennas.

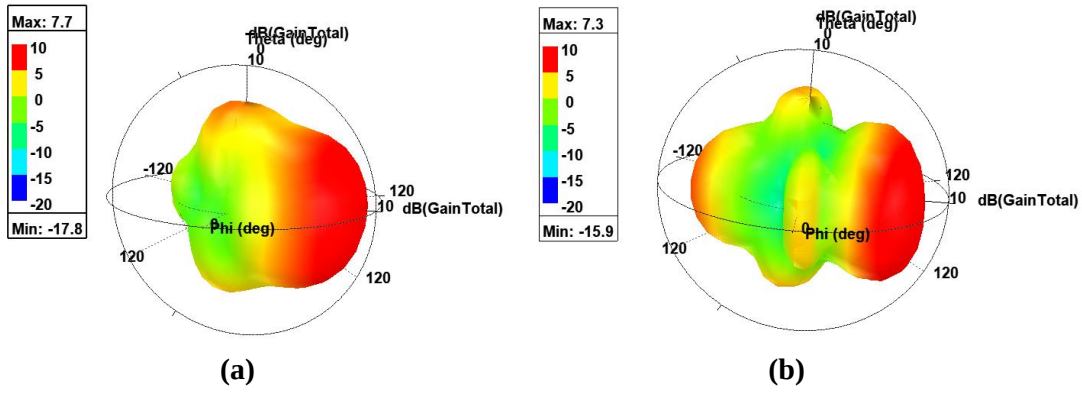


Figure 2.4: Gain comparison of (a) SICL and (b) CPS fed dipole antenna.

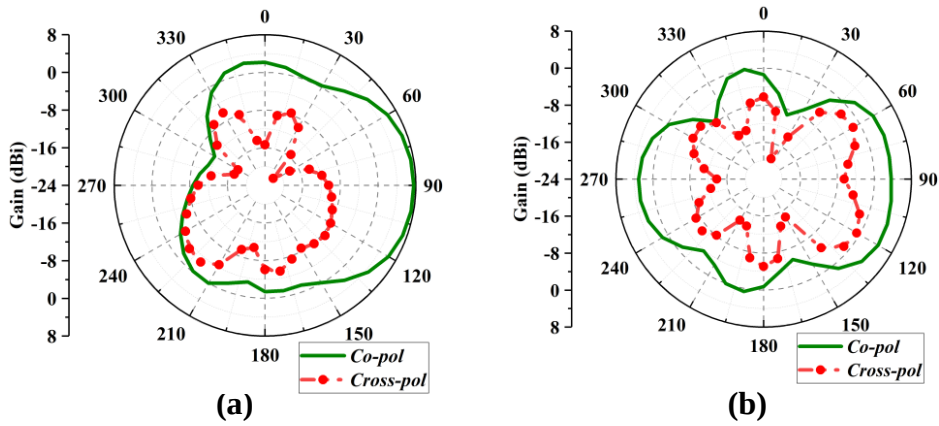


Figure 2.5: Radiation pattern in ($\phi=90^\circ$ plane) comparison of (a) SICL and (b) CPS fed dipole antenna.

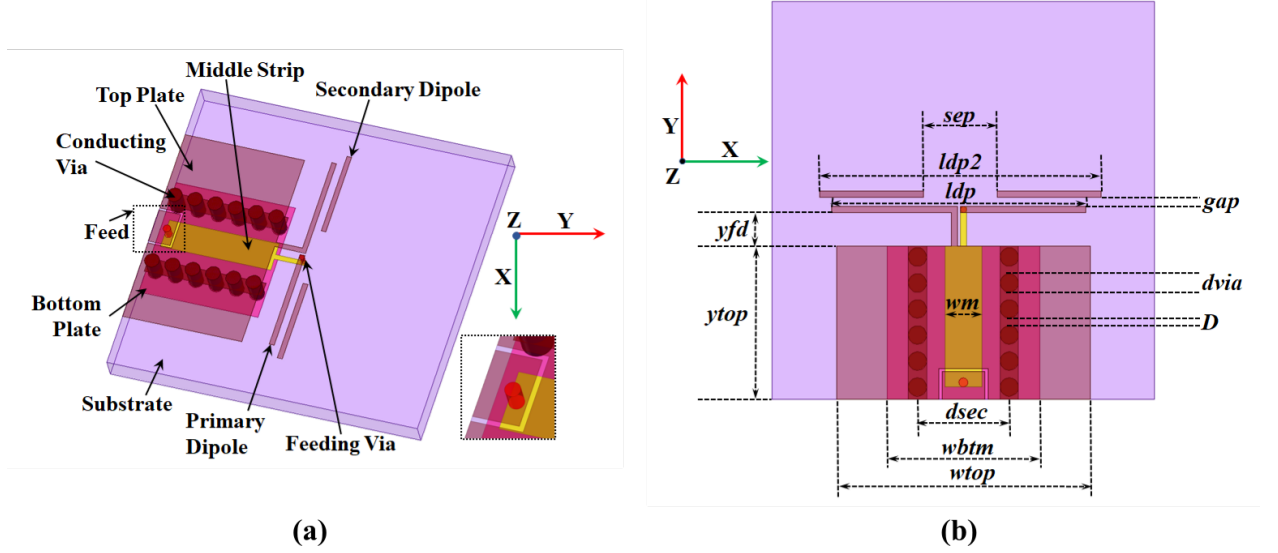


Figure 2.6: (a) Design and (b) geometrical layout of the proposed SICL fed broadband dipole antenna; inset-transition from GCPW to SICL transmission line.

2.3 Design of Substrate Integrated Coaxial Line based Broadband Dipole Antenna

In this section, the design of a broadband dipole antenna fed by the Substrate Integrated Coaxial Line (SICL) to work in Local Multipoint Distributed System (LMDS) band is discussed. The proposed broadband dipole antenna design utilises parasitic dipole in addition to the primary dipole antenna to enhance bandwidth. This antenna exhibits a broadband gain of 7.6 ± 0.4 dBi and 19% impedance bandwidth ranging from 25.7 GHz to 31.2 GHz. The proposed antenna finds its application in LMDS (26 GHz - 29 GHz) systems and millimetre wave applications.

2.3.1 Design and Principle of Operation

The design of the proposed broadband dipole antenna consists of two dipoles each of width 0.2 mm on substrate of size 12.5 mm x 13 mm. The layout of the antenna design is shown in Fig. 2.6 with the dimensions of design parameters listed in Table 2.1. The SICL transmission line feeds the first dipole directly with a line of length yfd . The middle strip with width w has a length of 4.6 mm that is fed by GCPW through a via as shown in Fig. 2.6(a) (inset). The width of the top plate (w_{top}) is kept larger than width of the bottom plate (w_{btm}) to act as reflector for backward waves from the dipole antenna. However, the length of both the top and the bottom plate (y_{top}) is

Table 2.1: Design parameters and dimensions of the proposed SICL fed broadband dipole antenna

Design Parameter	Dimension (in mm)	Design Parameter	Dimension (in mm)
w_{top}	8.6	D	0.25
w_{btm}	5	yfd	1.1
d_{sec}	3	gap	0.3
w	1.2	ldp	8.3
y_{top}	5	$ldp2$	9.2
d_{via}	0.6	sep	2.4

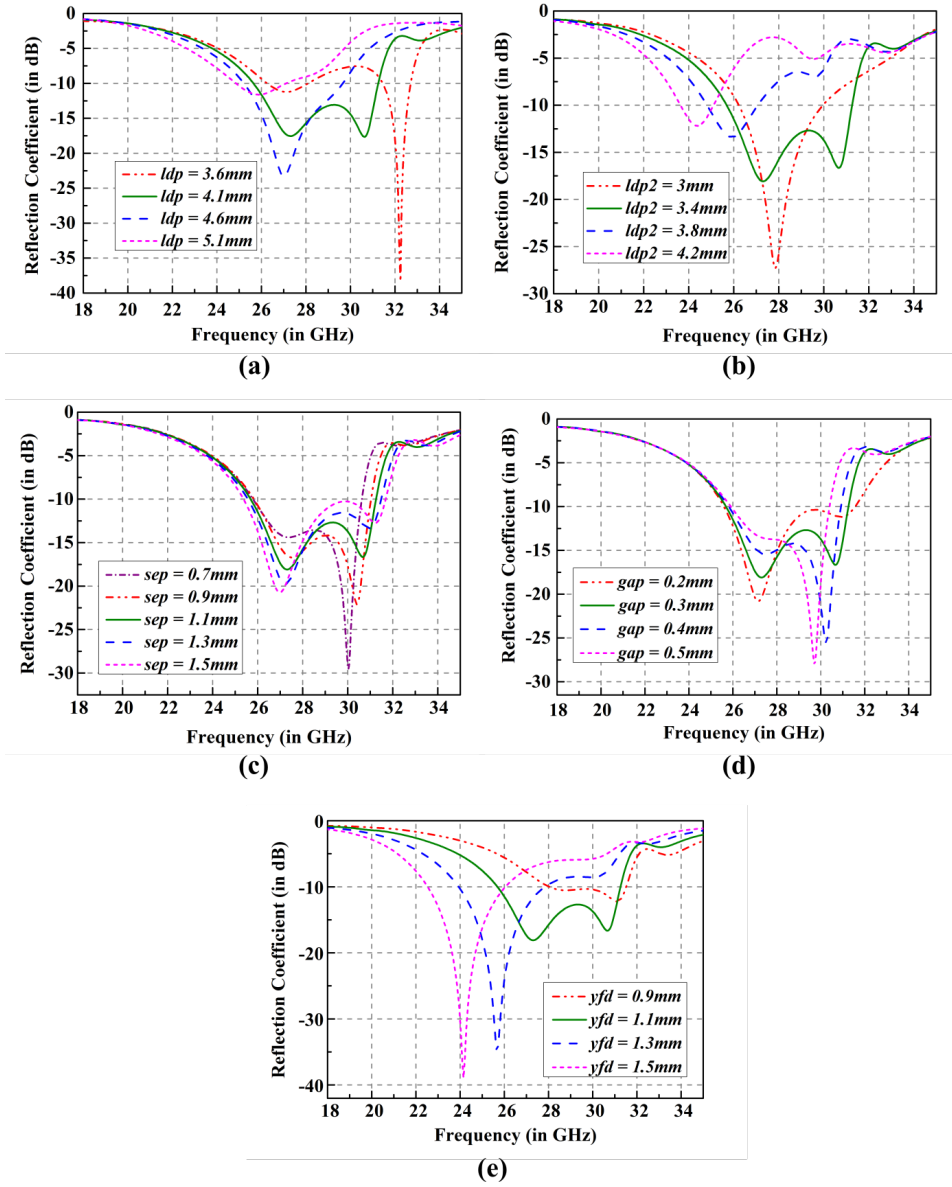


Figure 2.7: Variation of reflection coefficient with change in (a) length of primary dipole (ldp), (b) length of secondary dipole ($ldp2$), (c) separation of secondary dipole (sep), (d) gap between the primary and secondary dipole (gap) and (e) length of line feeding the primary dipole (yfd).

same. The middle strip then feeds the one of the arm of the first dipole through a *FeedingVia* as shown in Fig. 2.6(a). This implements the 180° phase shifter in the feeding section. Thereby, the SICL feeding section in itself acts as balun and thus eliminates the need to have a separate complex structure of balun and reflector as used in [Zhang and Xin, 2009]. The other arm of the first dipole is connected to the top plate by line of length yfd . The second dipole named as *SecondaryDipole* in Fig. 2.6(a) (with length $ldp2$), is kept at a distance (gap) from the first dipole. The distance (gap) and the separation (sep) of the secondary dipole is adjusted to achieve broadband performance of the desired frequency range.

2.3.2 Parametric Analysis of Antenna Design Parameters

The dimensions of the SICL transmission line in the feed section is chosen to keep the characteristic impedance 50Ω [Mukherjee, 2017b]. Parametric study has been carried for the

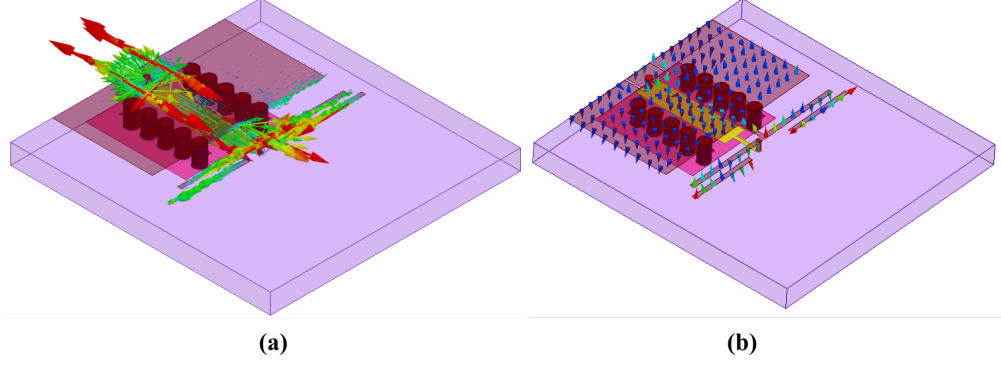


Figure 2.8: (a) Vector electric field and (b) surface current in top and middle layer of SICL feeding section and in the primary and secondary dipoles of the proposed antenna at 28 GHz.

dimensions yfd , gap , ldp , $ldp2$ and sep . The length of the primary dipole (ldp) is chosen greater than half-wavelength due to the loading effect of the second dipole. The lower resonant frequency shifts towards lower frequencies as the primary dipole length is increased. The broad bandwidth is obtained when ldp is chosen to be 4.1 mm as shown in Fig. 2.7(a). The second crucial parameter under study is the length of the secondary dipole ($ldp2$). As shown in Fig. 2.7(b), the length of parasitic dipole provides broad bandwidth in the desired frequency range. The upper resonant frequency decreases as the length $ldp2$ is increased. The third crucial parameter is the separation of the secondary dipole arms (sep). The two resonant frequencies from the dipole must be close enough in their vicinity to give the antenna broadband nature. This is observed when the parameter sep is 1.1 mm, the reflection coefficient of the two resonant frequencies below -15 dB as shown in Fig. 2.7(c). This dimension is used in the design for the optimum matching. The secondary (parasitic) dipole is excited by the primary dipole in phase, so that the resultant field constructively add to give the endfire radiation with high gain. The parametric study for the gap between the primary and secondary dipole as shown in Fig. 2.7(d) shows that gap of 0.3 mm gives the broadband radiation along with two resonant peaks from the two dipole. The length of the line feeding the primary dipole ($yfd < \lambda_g/4$) is an important parameter which controls the shift in the resonance as shown in Fig. 2.7(e). The above discussed parameters controls the broadband functioning of the dipole antenna. Careful adjustments in these parameter values completes the design of a broadband antenna.

2.3.3 Results and Discussion

The dipole antenna proposed here consist of primary and the secondary dipole where the secondary is the parasitic dipole and gets excited by the radiated field in primary dipole. The current and electric field distribution is shown in Fig. 2.8. A comparison is made between a single SICL fed dipole antenna and the proposed broadband dipole antenna that appreciates the bandwidth enhancement achieved in the proposed design. The single dipole antenna resonates at a single frequency of 28 GHz while exhibiting a gain of 7 dBi as designed in [Mukherjee, 2017b]. On the other hand, the proposed design of the broadband dipole antenna achieves a broad bandwidth of 6.7 GHz (24.5 - 31.2 GHz) with approximately stable gain of 7.6 ± 0.4 dBi. The evaluation of these antennas is presented by comparison shown in Fig. 2.9. It is evident that the use of secondary (parasitic) dipole increases the bandwidth of the antenna. The gain of the proposed SICL fed broadband dipole antenna is shown in Fig. 2.9. The observed front to back ratio (FTBR) is 12.2 dB. The substrate is extended beyond the secondary dipole which increases the gain, as the waves do not suffer a change in boundary due to dielectric-air interface. The radiation pattern is shown in Fig. 2.10. The proposed antenna exhibits endfire radiation pattern with half power beam width (HPBW) of 112° in E-plane and 50° in H-plane that meets the requirements of coverage

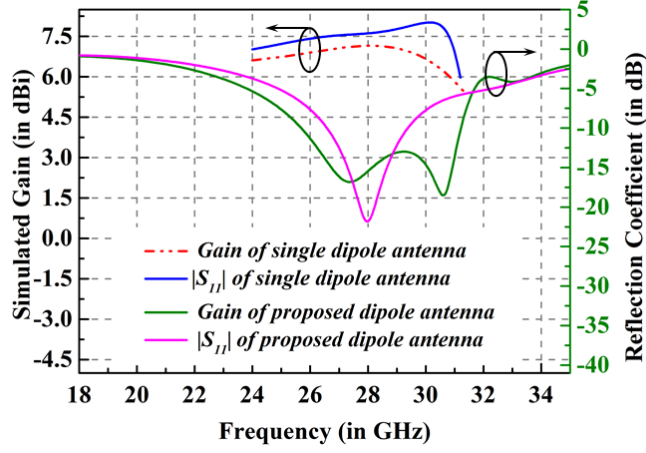


Figure 2.9: Comparison between SICL fed dipole antenna with and without secondary dipole.

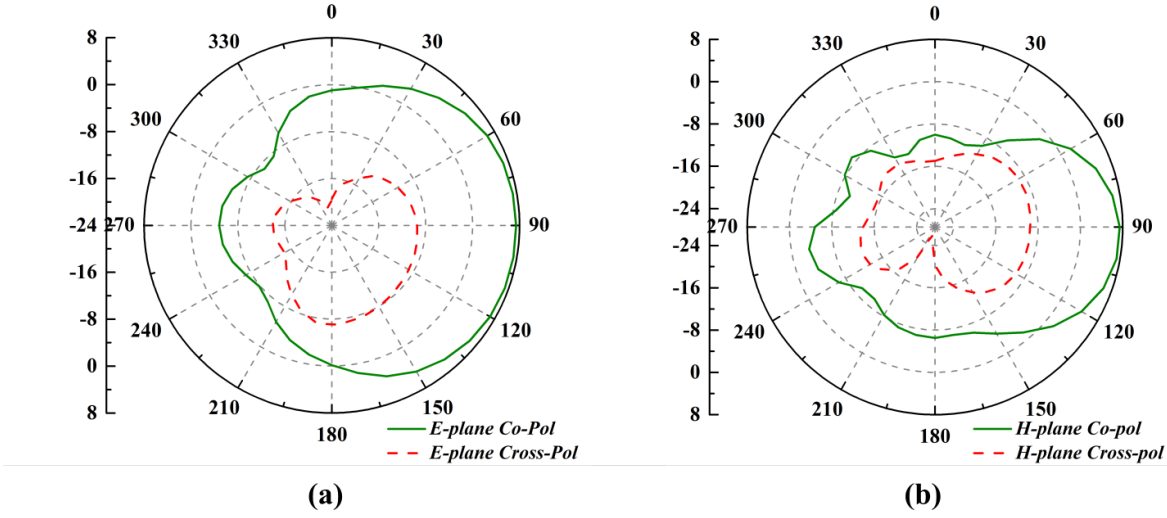


Figure 2.10: Radiation pattern of the proposed SICL fed broadband dipole antenna at 28 GHz in (a) E-Plane ($\phi = 90^\circ$) and (b) H-Plane ($\theta = 90^\circ$).

sector of LMDS transmitter as specified in [Nordbotten, 2000].

2.4 Design of Substrate Integrated Coaxial Line fed Quasi Yagi Antenna

In this Section, the design of a printed Quasi-Yagi Antenna with Substrate Integrated Coaxial Line (SICL) feed network working in the millimetre frequency range is discussed. The proposed antenna realized in SICL can be fabricated using traditional PCB technology. SICL feeding section makes the antenna design simple, surpasses the need to have balun and reflector. The antenna has been designed to operate at 26 GHz with a wide bandwidth performance of 6.3 GHz, providing a gain of 7.2 dB and Front to Back Ratio of better than 21 dB. The SICL section exhibits good shielding ability which is advantageous for circuits implemented in millimeter wave frequency range. The out-of-phase current in the middle and top layer of SICL reduces complexity in feed network by eliminating balun and makes the design compact which is a crucial requirement

Table 2.2: Design parameters and dimensions of the proposed SICL fed Quasi-Yagi antenna

Design Parameter	Dimension (in mm)	Design Parameter	Dimension (in mm)
S_{sub}	2.5	L_{strip}	1
$W_{dir} = W_{dip}$	0.2	W_{strip}	1.2
$s1$	4.17	$W1$	1.6
L_{dip}	6.3	W_{bottom}	5
L_{plate}	4	D	0.6
s	0.25	L_{dir}	3.4

at millimetre wave applications.

2.4.1 Design and Principle of Operation

The geometrical layout of the proposed Quasi-Yagi antenna is shown in Fig. 2.11. Two 12 mm x 15 mm Taconic TLY-5A substrates (thickness of 1mm, $\epsilon_r = 2.2$) are bonded together using Taconic FR-28 bond layer for designing the antenna. The Quasi-Yagi antenna consists of a dipole and a director, where the director is placed at 4.12 mm apart from the dipole in the endfire direction to increase the directivity of the radiated beam. The dipole of length L_{dip} is fed by SICL using an feeding arm $d1$ between SICL feed structure and driven dipole element. The two half dipoles are connected to the top plate and middle strip through a feeding via respectively. As shown in Fig. 2.11, the middle strip is connected to the dipole arm using *FeedingVia* through the substrate. The design parameters is shown in Fig. 2.11. The length of the dipole (L_{dip}), vias separation (s), vias diameter (D) and length of the director (L_{dir}) is tuned to resonate the antenna in the desired frequency range. The pitch ratio ($s/D < 2$) of the metallic via is maintained to achieve proper shielding effect as in a Substrate Integrated Waveguides. The Substrate Integrated Coaxial Line (SICL) feeding network consists of two layers of dielectric with conductor plate at the top and bottom of the dielectric substrate while the middle conductor strip is sandwiched between the conducting plate. The two rows of metallic vias provide the side wall shielding as in the case of a rectangular coaxial line(RCL). The dimensions of the SICL are chosen to keep its characteristic

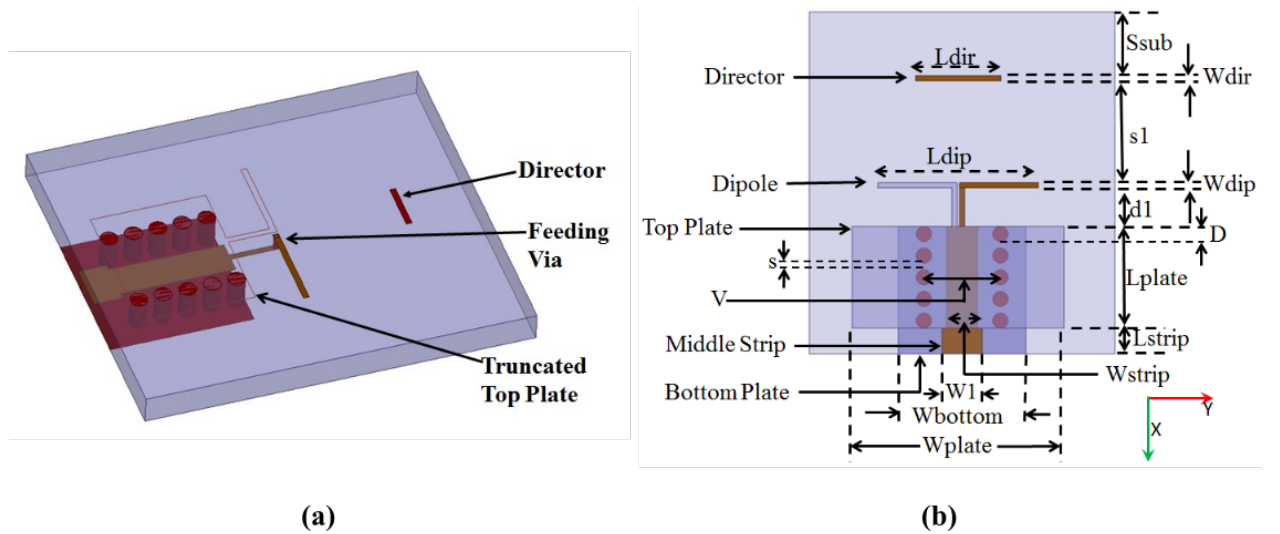


Figure 2.11: (a) Design and (b) geometrical layout of the proposed SICL fed Quasi-Yagi antenna.

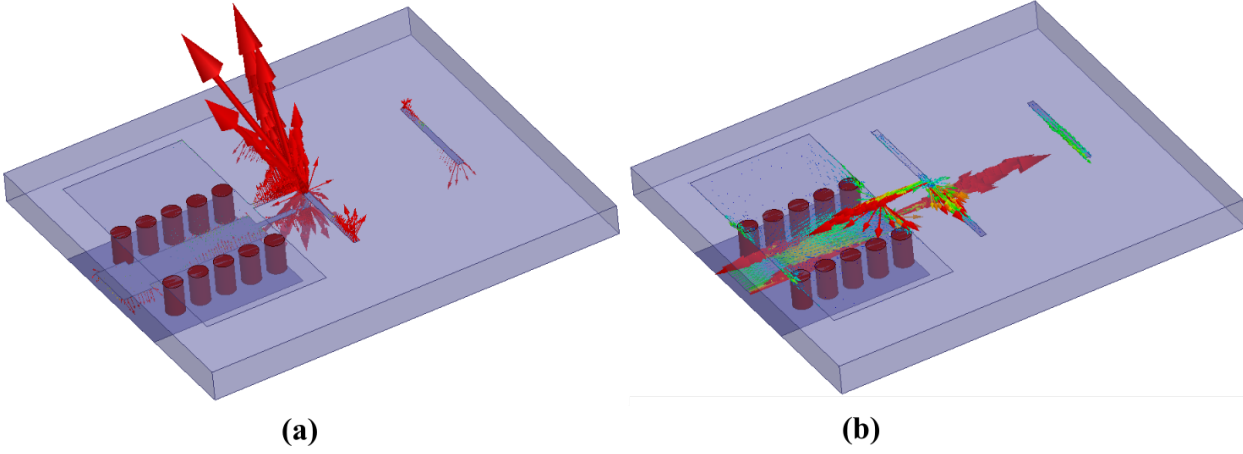


Figure 2.12: (a) Vector electric field and (b) vector surface current in top, middle layer and director of the proposed antenna at 28 GHz.

impedance of 50Ω [Mukherjee, 2017b]. Metal conducting vias of diameter (D) 0.6 mm is placed along the length of the middle strip on either side. The metallic vias connect the truncated top plate & bottom plate which acts as the shielded outer conductor. The calculations of dimensions are determined considering the change in dielectric constant (ϵ_r) at higher frequency [Gatti *et al.*, 2006]. The guided wavelength (λ_{eff}) is expressed by the relation given by [Gupta and Bhartia, 1996] as:

$$\lambda_{eff} = \frac{c}{f\sqrt{(\epsilon_{re} \cdot f)}} \quad (2.1)$$

where, $\epsilon_{re}(f)$ given by [Gupta and Bhartia, 1996] as:

$$\epsilon_{re}(f) = \epsilon_r - \frac{\epsilon_r - \epsilon_{re}(0)}{1 + P(f)} \quad (2.2)$$

where , $\epsilon_{re}(0)$ is the effective dielectric constant given as:

$$\epsilon_{re}(0) = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-1/2} \quad (2.3)$$

$$P(f) = P_1 P_2 \{0.1844 + P_3 P_4 10fh\}^{1.5763} \quad (2.4)$$

$$P_1 = 0.27483 + \left\{ 0.6315 + \frac{0.525}{(1 + 0.157fh)^{20}} \right\} \left(\frac{W}{h} \right) - 0.065683e^{(-8.7513 \frac{W}{h})} \quad (2.5)$$

$$P_2 = 0.33622 \left\{ 1 - e^{(0.03442\epsilon_r)} \right\} \quad (2.6)$$

$$P_3 = 0.33622 \exp(-4.6 \frac{W}{h}) \left[1 - \exp \left\{ - \left(\frac{fh}{3.87} \right)^{4.97} \right\} \right] \quad (2.7)$$

$$P_4 = 1 + 2.75 \left[1 - \exp \left\{ - \left(\frac{\epsilon_r}{15.916} \right)^8 \right\} \right] \quad (2.8)$$

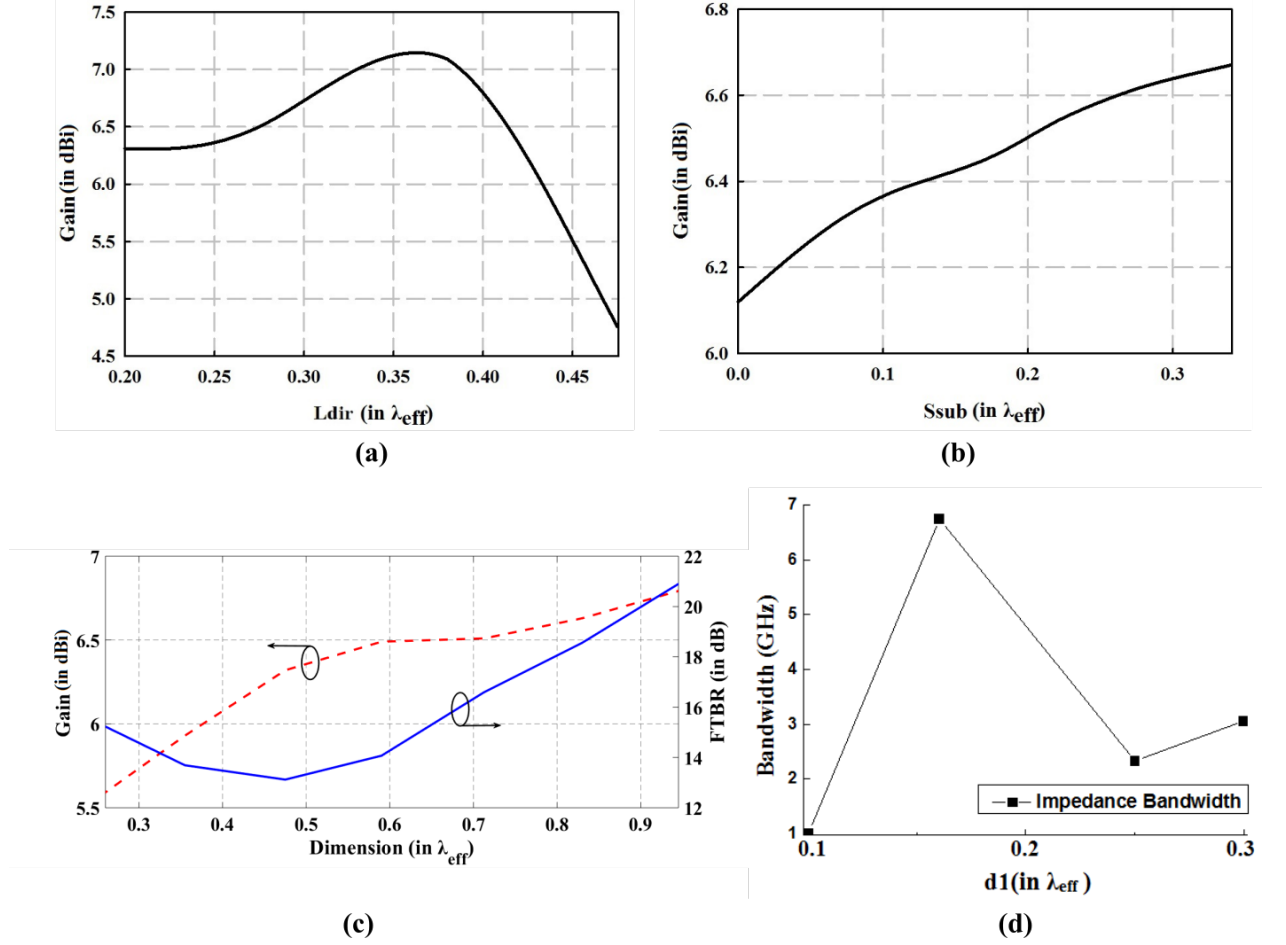


Figure 2.13: Variation in gain of the antenna with (a) length of the director (L_{dir}), (b) dielectric extension (S_{sub}). (c) Variation in FTBR and gain with director to dipole distance ($s1$) and (b) variation in bandwidth with dipole to top plate distance ($d1$).

where h , W are expressed in cms, f in GHz. The distance between the two via sections is W , the separation between the two adjacent vias is s and the diameter of the via is D as shown in Fig. 2.11(b), then the cut-off frequency [Kaneda *et al.*, 2002] is given by:

$$f = \frac{c}{2\sqrt{\epsilon_r}} \left(A - \frac{D^2}{0.95S} \right)^{-1} \quad (2.9)$$

The proposed feeding network works as efficient as a coaxial cable to feed the Quasi-Yagi antenna operating in Ka-band. The parasitic director is placed at distance less than $0.48\lambda_{eff}$ from the driven dipole element and the arm connecting the driven dipole element is placed at $0.17\lambda_{eff}$ from the SICL feed section (metallic top plate). Due to the TEM wave propagation in the feeding network the surface current through the middle layer is 180° out of phase of that in the top plate. This eliminates the need to have a 180° phase shifter as in [Farrall and Young, 2004]. The vector electric field and surface current in the top and middle layer of proposed antenna is shown in Fig. 2.12. In the proposed design, out of phase surface current of SICL section replaces the balun in the feeding network of conventional printed dipole antenna.

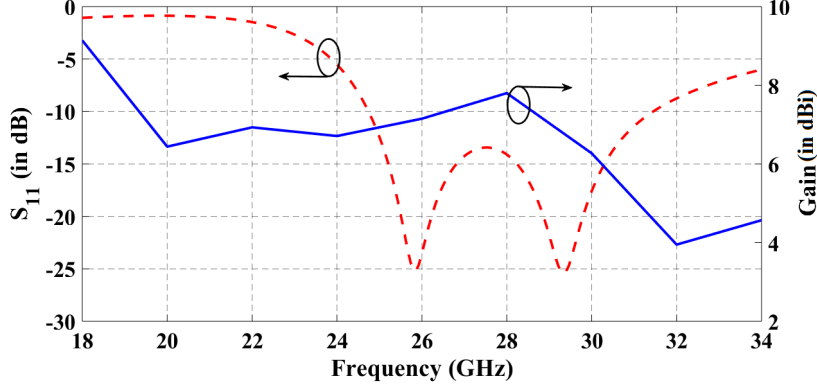


Figure 2.14: Simulated gain and reflection coefficient response in Ka Band.

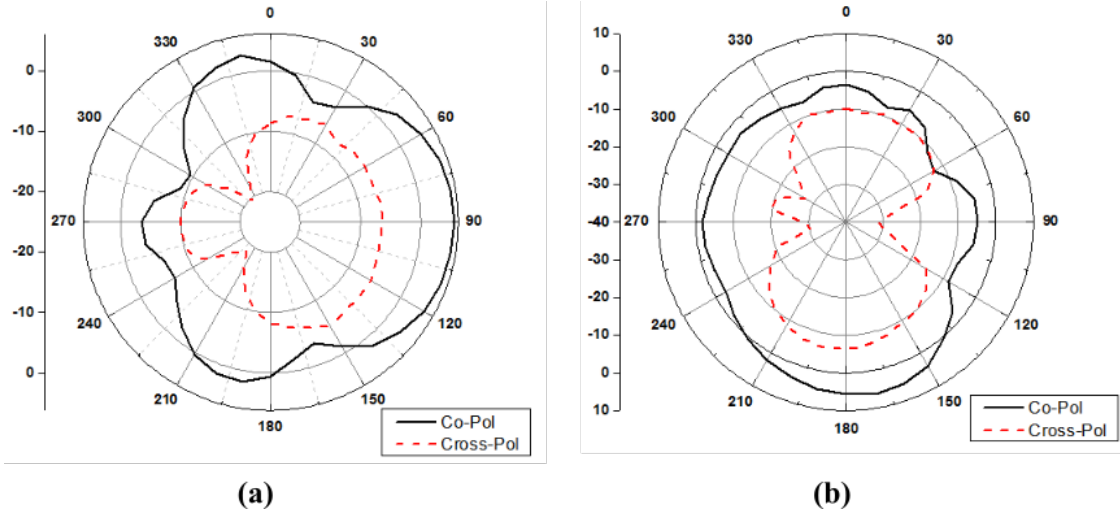


Figure 2.15: Radiation pattern of the proposed SICL fed Quasi-Yagi antenna at 28 GHz in (a) E-Plane ($\phi = 180^\circ$) and (b) H-Plane ($\theta = 90^\circ$).

2.4.2 Results and Discussion

With SICL feed, we are able to simplify the feeding network and make the design compact in a smaller footprint. Furthermore, it is worth noting that the SICL fed planar Quasi-Yagi Antenna exhibits superior performance in terms of gain and enhanced Front to Back Ratio compared to the previously mentioned research [Farrall and Young, 2004]. In order to achieve better front to back ratio (FTBR), the design parameter W_{plate} i.e., width of the top metallic plate reflector has been studied. It becomes evident from the observations that in order to enhance FTBR, it is advisable to have the width of the metallic plate (W_{plate}) slightly greater than the length of the dipole elements and must be kept in terms of $1.0 \times \lambda_{eff}$. In this design, the width of the truncated top plate W_{plate} is chosen to be 8.3 mm ($\lambda_{re}(f) = 1.73$, $\lambda_{eff} = 8.77$ mm) as shown in Fig. 2.11. The variation in the gain of the antenna with the change in the length of the director (L_{dir}) is studied. The gain is observed to gradually increase till length of $L_{dir} 0.4\lambda_{eff}$ after which it will decrease as shown in Fig. 2.13(a).

Besides, the enhancement in the antenna design parameters have been carried out to find the optimal size of the antenna to achieve a high gain with improved FTBR. Extending the substrate beyond the director shows an improvement in gain as shown in Fig. 2.13(b). This phenomenon is attributed to the propagation of the wave within the dielectric medium, where the absence of an abrupt

mismatch between the dielectric and air interfaces allows for uninterrupted wave propagation. The gain however increase much slowly with the dimension (S_{sub} , the extension of the substrate beyond the director). Another parameter $s1$ (director to dipole spacing) showed an improvement in the gain of the antenna as in Fig. 2.13(c). This is because the parasitic director element placed in line with the dipole directs the radiation towards endfire direction. However, it showed gradual improvement in the gain as $s1$ is increased. The design with dimensions listed in table are chosen to achieve proper matching with feed section, high gain and better front-to-back ratio. Fig. 2.13(d) shows that the distance between the SICL feeding section and driven dipole element ($d1$) affects the matching characteristics of the antenna. The simulated reflection coefficient $|S_{11}|$ and gain is shown in Fig. 2.14. The simulated results show the matching of the antenna with SICL feed at 26 GHz frequency with -10 dB bandwidth of 6.38 GHz. The radiation pattern in E-plane and H-plane at 26 GHz is shown in the Fig. 2.15. The gain of the antenna is 7.2 dB with cross-pol 17.9 dB below the co-Pol component in both E-plane and H-plane, with front to back ratio (FTBR) of 21 dB.

2.5 Design of Substrate Integrated Coaxial Line (SICL) Excited Wideband Millimeter Wave Bow-Tie Antenna

In this Section, the design of the bow-tie antenna with substrate integrated coaxial line (SICL) is presented. Bow-Tie antennas are often used for television reception, RFID systems, and other wireless communication applications. They are known for their wide bandwidth and omnidirectional characteristics. Substrate Integrated Coaxial Line provides wide bandwidth for the dominant TEM mode of operation. The proposed Bow-Tie antenna excited by SICL exhibits a wide 10 dB impedance bandwidth of 8.7 GHz with an average gain of 4.5 dBi in the entire frequency band. As seen in previous sections, one advantage of using SICL feeding network is the elimination of balun as required in the microstrip technology to feed the antenna. Another advantage is the wideband performance in SICL which is difficult to be obtained with its counterpart namely, Substrate Integrated Waveguide (SIW). SICL ground plate acts as reflector and reflects the backward wave, making the radiated beam endfire. The end-fire radiation pattern of the proposed antenna shows co-polarization to cross polarization ratio of 13.7 dB at the center frequency. The antenna is suitable for 5G applications at 5G millimeter wave frequencies beyond 24 GHz and applications in the LMDS band.

2.5.1 Design and Principle of Operation

The proposed antenna is designed on Rogers RT/Duroid 5880 substrate (thickness of 1 mm, $\epsilon_r = 2.2$) of size 12 mm x 11.75 mm. One arm of the Bow-Tie is fed by the top plate of the SICL with feedline $t3$, while the other arm of the antenna is excited by the central conductor using *Connect Via* as shown in Fig. 2.16(a). Thereby broadside-coupled stripline (BCS) configuration introduces the necessary 180° phase difference between the two arms of the antenna. This reduces the total size of the antenna and makes the design compact.

For connecting 50 Ω coax connector, a grounded coplanar waveguide (GCPW) is used as the transitional element between SICL and coax connector. The design consists of GCPW line, SICL transmission line and the Bow Tie antenna. The Bow-Tie antenna is similar to the half-wavelength ($\lambda_g/2$) dipole antenna, where the dimensions of the antenna depends on the angle of the Bow and half wavelength of the operating frequency. The design parameters are shown in Fig. 2.16(b). The length of the antenna Lb is kept 3.18 mm which is approximately half-wavelength ($\lambda_g/2$) at the center frequency. The dependence of the antenna dimension on the Bow angle provides wide fractional bandwidth. The Bow angle (α) is controlled by the dimension $t4$. As shown in Fig. 2.17, an increase in the Bow angle achieved by increasing $t4$ widens the bandwidth of the antenna.

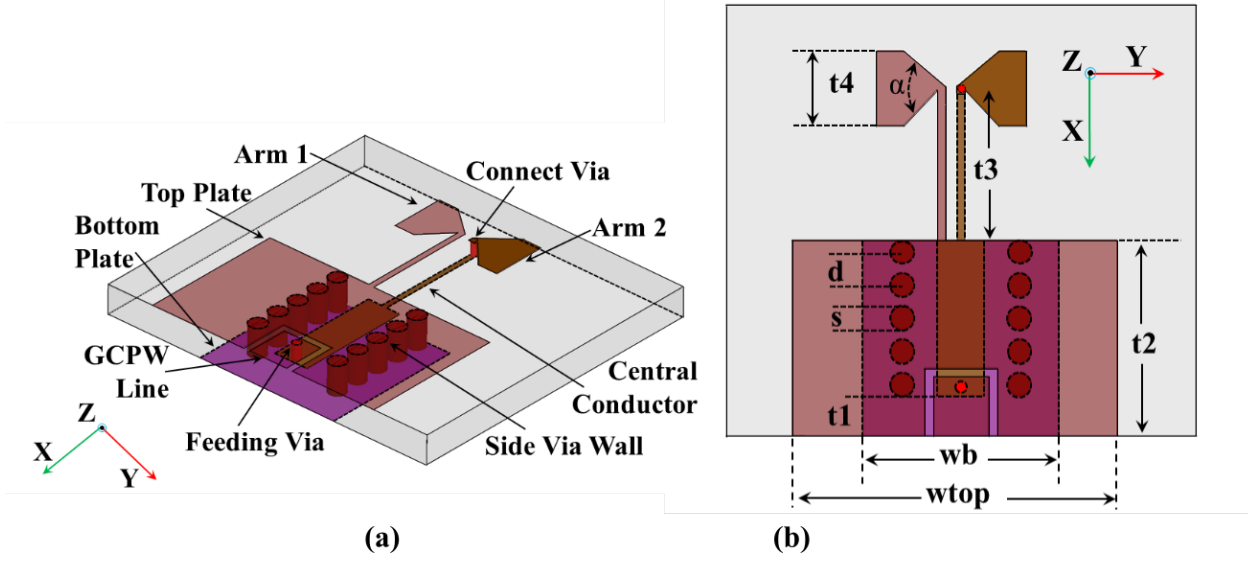


Figure 2.16: (a) Design and (b) geometrical layout of the proposed SICL excited Bow-Tie antenna. Dimensions (in mm): ($t_1 = 12.6$, $t_2 = 5$, $t_3 = 9.8$, $t_4 = 0.9$, $w_{top} = 1.6$, $w_b = 1.2$, $d = 0.9$, $s = 0.6$, $L_b = 3.81$).

Hence, to obtain broad bandwidth, this parameter must be carefully chosen. Another important parameter is the length of the transmission line feeding the antenna (t_3). The top plate of the SICL section acts as the reflector for the antenna. The reflector must be placed at quarter wavelength ($\lambda_g/4$) distance from the antenna to obtain constructive interference of the reflected wave with the forward wave. It is observed that the average gain of the antenna changes from 3.8 dBi to 5 dBi upon varying the length t_3 . Thus, for designing the Bow-Tie antenna attention must be paid to determine the distance of the antenna from reflector. The magnitude of electric field and the

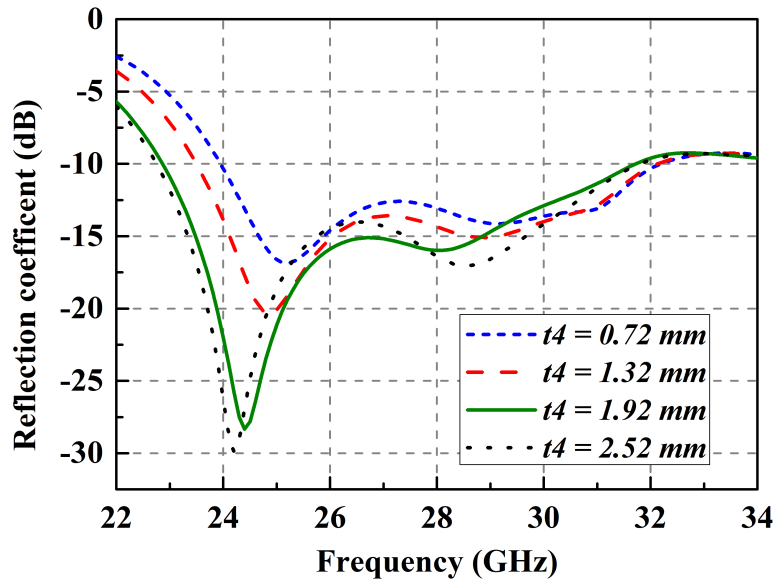


Figure 2.17: Variation in reflection coefficient with parameter t_4 for the Bow angle () of the proposed SICL excited Bow-Tie antenna.

vector surface current exciting the Bow-Tie antenna is shown in Fig. 2.18 which shows the shielded nature of the SICL transmission line. Both the arms of the antenna are placed on the top side of the substrate. Due to the inherent nature of SICL, out of phase current distribution in the central conductor with respect to the top and the bottom plate is achieved.

2.5.2 Results and Discussion

The 10 dB impedance bandwidth of the designed antenna is 8.7 GHz (from 23.6 GHz to 32.3 GHz) as shown in Fig. 2.19. The fractional impedance bandwidth of 31% is obtained for the proposed Bow-Tie antenna. The average gain of the antenna is 5 dBi in the entire operating bandwidth. The E-plane and H-plane radiation pattern are shown in Fig. 2.20. The co-polarization is 13.7 dB above the cross-polarization at the center frequency. Due to the presence of reflector (top plate of the SICL section), the radiation pattern is suppressed at the back. With SICL feed section, we are able to achieve a compact and shielded design for the proposed antenna.

2.6 Design of SICL fed Dual Polarized Dipole Antenna

In this Section, a novel design of dual polarized dipole antenna fed by Substrate Integrated Coaxial Line (SICL) is presented for Ka-band application. Dual polarization is achieved using two orthogonal radiating dipole antennas. A middle dipole arm common for the top -45° tilted dipole arm printed on the top and $+45^\circ$ bottom dipole arm printed on the bottom sides of the substrate enables compactness in the proposed antenna design. PIN diode is utilized in the feeding line to control the polarization of the antenna. Hence by switching the PIN diodes between dipole antennas, the dominant TEM mode of SICL is simultaneously excited in the antenna and dual linear polarization is obtained. The proposed antenna resonates at 28.1 GHz exhibiting gain of 4.9 dBi for the two polarizations and co-pol to cross-pol ratio is better than 20 dB. This antenna is a suitable candidate for 5G millimeter wave applications.

2.6.1 Design

The proposed design consists of three segments, namely SICL feeding network, beam switching feed line with PIN diode and orthogonal tilted dipole antenna as shown in Fig. 1(a). The proposed antenna is designed on two Taconic TLX-5A substrate 10 mm x 12.5 mm (height of 0.5mm each, $\epsilon_r = 2.2$) bonded together using Taconic FR-28 bond layer (height 0.1 mm, $2.75 < \epsilon_r < 2.9$)

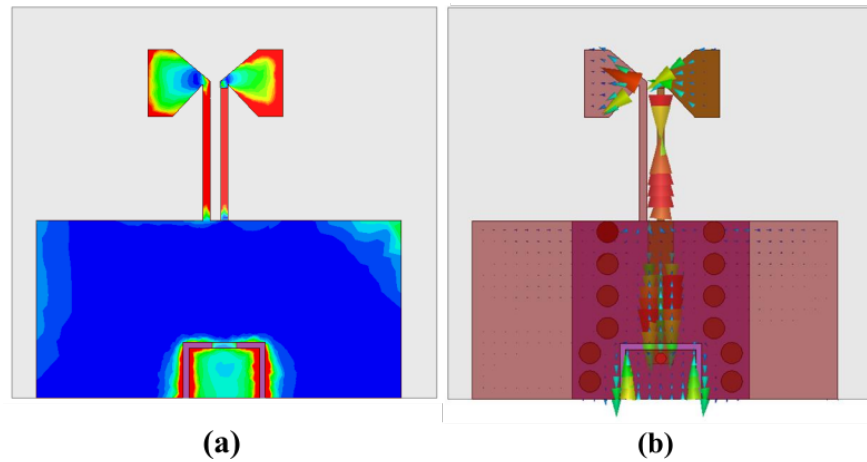


Figure 2.18: (a) Magnitude of electric field distribution and (b) vector surface current distribution in both the arms of the proposed SICL excited Bow-Tie antenna at the center frequency.

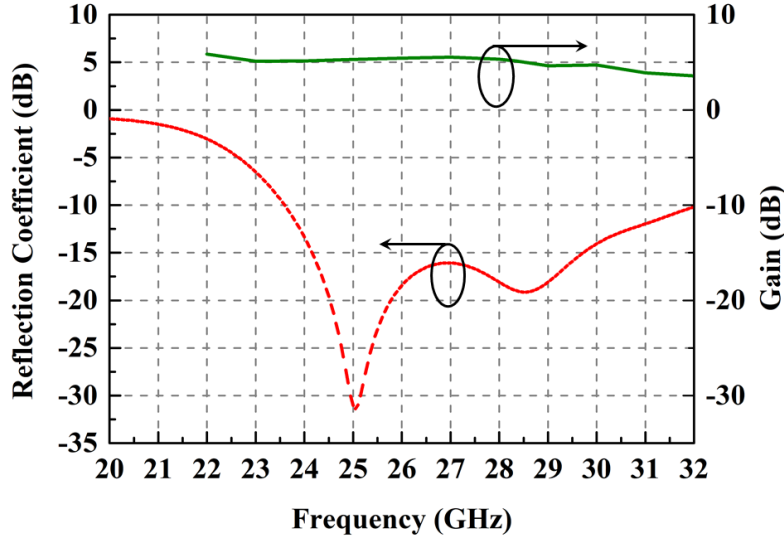


Figure 2.19: The reflection coefficient and gain plot of the proposed SICL excited wideband Bow-Tie antenna.

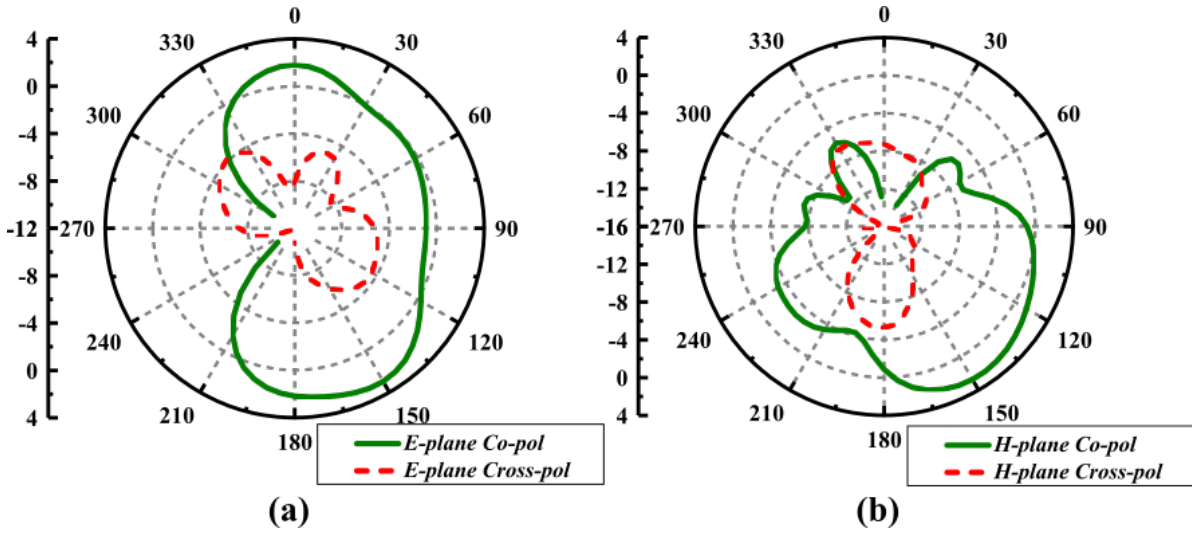


Figure 2.20: (a) E-plane at $\phi = 180^\circ$ and (b) H-plane at $\theta = 90^\circ$ radiation pattern for proposed SICL excited Bow-Tie antenna at 28 GHz.

to form a planar structure.

2.6.1.1 SICL Feeding Network

The Substrate Integrated Coaxial Line (SICL) transmission line consists of a middle plate sandwiched between top and bottom plates. To provide the sidewall shielding as in coaxial line, two rows of electroplated via-walls encapsulating the middle plate runs throughout the transmission line [5]. The shielded nature of SICL makes it highly suitable for designing antennas. A GCPW (Grounded Co-Planar Waveguide) to SICL transition as shown in Fig. 2.21(a) is used to excite the TEM mode in the feeding network [Baghel and Mukherjee, 2020a]. Due to the TEM wave propagation in the feeding network the surface current through the middle plate is 180° out of phase of that in the top and bottom plate.

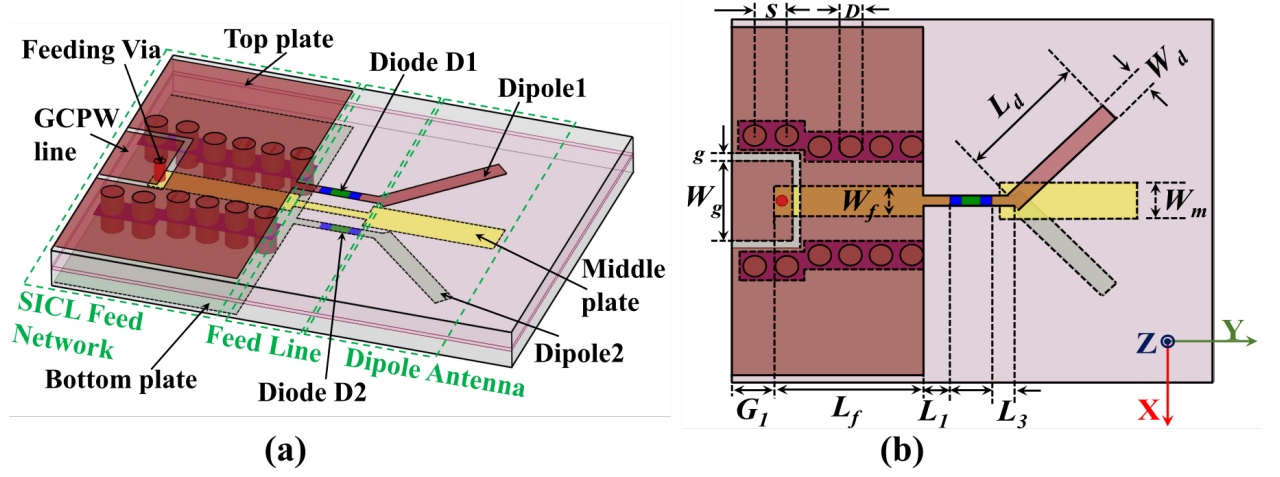


Figure 2.21: (a) 3D trimetric view and (b) top view of the proposed SICL fed dual polarized dipole antenna. The dimensions are (in mm) : $g = 0.2$, $W_g = 2.1$, $W_f = 0.85$, $G_1 = 1.1$, $L_f = 3.9$, $L_1 = 0.8$, $L_2 = 1$, $L_3 = 0.6$, $W_d = 0.5$, $L_d = 3.6$, $W_m = 1$, $s = 0.9$, $D = 0.6$.

2.6.1.2 Feed Line with PIN diode

The middle segment of the design consists of PIN diode that enables the switching in the antenna. Two PIN diodes (MA4P907) labelled as D1 and D2 shown in Fig. 2.21(a) are integrated in the feeding line to control the polarization of the antenna. Each PIN diodes acts as a resistor in the ON-state and as a capacitor in the OFF-state. The diodes are placed at a distance of L_1 from the SICL feed network and L_3 from the antenna. To ensure constructive interference of the forward wave with the reflected wave from the SICL feeding network, the antenna must be placed at $\lambda_g/4$ (quarter wavelength) distance from the SICL feeding network. Hence, careful optimisation of the lengths L_1 and L_2 is performed.

2.6.1.3 Orthogonal Dipole antenna

A half wavelength ($L_d = \lambda_g/2$) dipole antenna is designed by printing one arm of dipole on top plate (*Dipole1*) /bottom plate (*Dipole2*) of the substrate and the other arm of dipoles connected to the common middle plate as shown in Fig. 2.21(a). The two arms of the dipole antennas printed on the top and the bottom side of the substrate are tilted with respect to the middle layer by $+45^\circ$ and -45° respectively. Thus, mutual orthogonality is achieved between the two dipole antennas.

Table 2.3: Summary of Working Principle with Switching States

Switching state	Diode	Conducting Path	Antenna
State1	D1 ON, D2 OFF	Top Plate, Middle Plate	Dipole1
State2	D1 OFF, D2 ON	Bottom Plate, Middle Plate	Dipole2

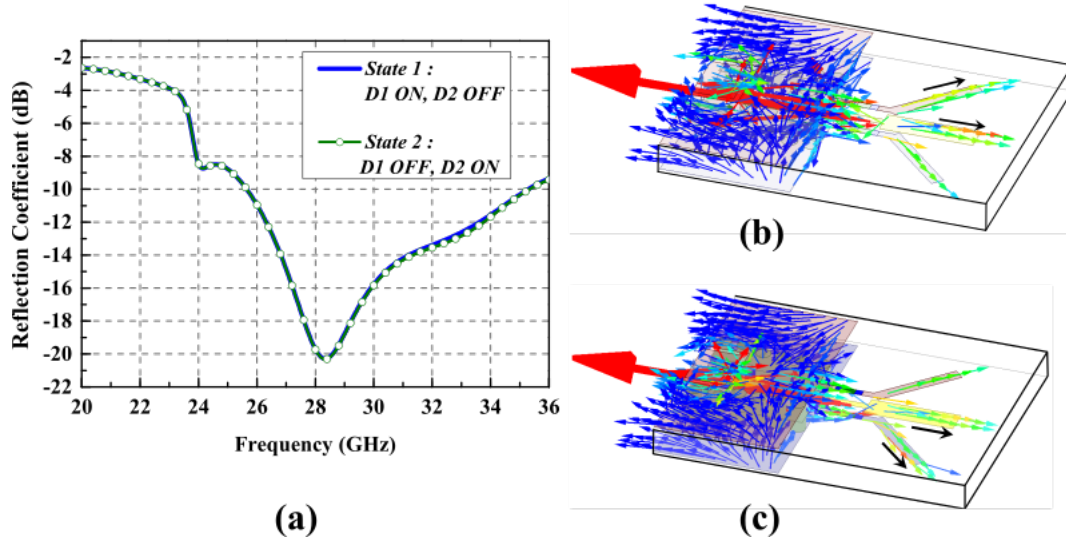


Figure 2.22: (a) Reflection coefficient, and surface current in top, middle and bottom layer at 28.1 GHz in (b) state 1 and (c) state 2 for the proposed SICL fed dual polarized dipole antenna.

2.6.2 Principle of Operation

Diode D1 provides the conducting path to the dipole in the top plate (*Dipole1*) and diode D2 provides the conducting path to the dipole in the bottom plate (*Dipole2*). When diode D1 is turned ON and diode D2 is turned OFF (*State1*), the current flows through the *Dipole1* in the top layer while *Dipole2* in the bottom plate is disconnected. Thus, first dipole antenna is excited and radiate into the free space. Next, when diode D1 is switched OFF and diode D2 is switched ON (*State2*), *Dipole1* is disconnected and current flows through the bottom path exciting the second dipole antenna and *Dipole2* radiates. Thus, activating the diodes alternatively enable the two mutually-orthogonal dipole antennas achieve dual polarization. The working principle of the proposed dual polarized dipole antenna is presented in Table 2.3.

2.6.3 Results and Discussion

In the proposed design, mutually-orthogonal dipole antennas is obtained using simultaneous switching of the diodes (D1, D2). The simulated reflection coefficient of the antenna is shown in Fig. 2.22(a). The two dipole antennas resonate at 28.1 GHz with 31.5% -10 dB impedance bandwidth at the center frequency. The vector surface current depicted in Fig. 2.22(b,c) shows the current flow in *Dipole1* and *Dipole2* for diode switching *State1* and *State2* respectively.

The radiation pattern of the proposed antenna is plotted in Fig. 2.23 keeping 45° tilt of the antenna into consideration. The antenna exhibits unidirectional radiation due to the presence of the extended ground plane of the SICL feeding network. The dipole antenna achieves a gain of 4.9 dBi at 28.1 GHz. The dual polarization is observed in the radiation pattern as seen in Fig. 2.23. Radiation pattern in Fig. 2.23(a,b) is depicted for E-plane ($\phi = 135^\circ$) /H-plane ($\phi = 45^\circ$) for switching *State1* and Fig. 2.23(c,d) for the E-plane ($\phi = 45^\circ$) /H-plane ($\phi = 135^\circ$) for switching *State2*. The co-pol to cross-pol ratio is better than 20 dB.

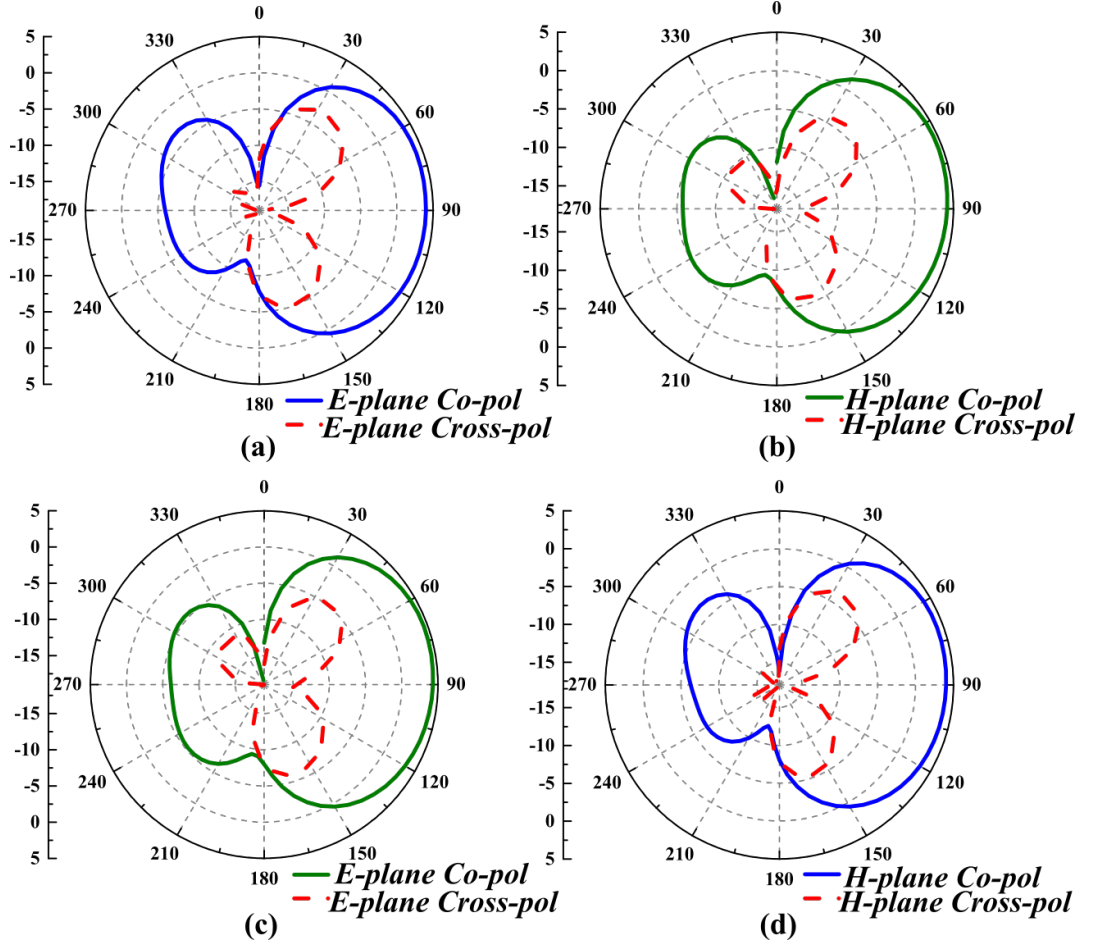


Figure 2.23: Radiation pattern for the proposed dual polarized SICL fed dipole antenna at 28.1 GHz for switching E-plane and H-plane for (a), (b) *State1* and (c), (d) *State2* of the diodes respectively.

2.7 Design of SICL fed Ka-band Dual Polarized Dipole Antenna Array

In this Section, a 1 x 4 dual polarized modified dipole antenna array fed by Substrate Integrated Coaxial Line (SICL) is presented for Ka-band applications. The proposed array is achieved using two orthogonal radiating dipole antennas employing the standard $\pm 45^\circ$ slant technique. The elementary antenna is implemented by two 45° tilted modified dipole antennas printed orthogonal to each other on the top plate of substrate. The other dipole arm is implemented using the middle plate of SICL feeding network. The polarization of the antenna is controlled by exciting the antenna through either of the two feeding ports. A 1 x 4 stacked array of proposed antenna using L-bend SICL feeding network is utilized to obtain a gain of 7.6 dBi while maintaining good isolation. The proposed antenna resonates at 26 GHz exhibiting wide impedance bandwidth for the two polarization and co-pol to cross-pol ratio better than 23 dB. As established in previous designs, SICL helps in achieving a compact design by eliminating balun to feed the two arms of the dipole. Moreover, the feed network is compact and attains good isolation due to shielding. Another advantage of designing the antenna in SICL technology is the improvement in front-to-back ratio (FTBR) caused by the reflection of back radiations from the ground plates of SICL feeding network. This antenna finds its utility in n258-NR (New Radio) 5G spectrum endfire applications centered around 26 GHz.

2.7.1 Design and Principle of Operation

The proposed antenna is designed on two Taconic TLY-5A substrate 10 mm x 12.5 mm (height of 0.5 mm each, $\epsilon_r = 2.2$) bonded together using Taconic FR-28 bond layer (height 0.1 mm, $2.75 < \epsilon_r < 2.9$) to form a planar structure.

2.7.1.1 Dual Polarized Dipole Antenna

The proposed dual polarized antenna consists of two orthogonal half wavelength ($L_d = \lambda_g/2$) inclined dipoles at $+45^\circ$ and -45° fed by the top plate of the Substrate Integrated Coaxial Line (SICL) using a small section of feeding line as shown in Fig. 2.24(a). The other arms of the two dipoles are connected to the middle plate of the SICL transmission line. The dimensions of the design parameter are mentioned in Fig. 2.24(b). This forms the elementary layer for the antenna array. The feeding line plays a vital role in excitation of the dipole radiator. The width of the feed line W_f provides optimum matching level and helps in impedance matching between the dipole antenna and the SICL feeding section. The length of the feed line L_f helps in tuning of the resonant frequency. The operating frequency of the antenna is largely dependent on the length of dipole arm and length of the feed line provides greater degree of freedom for fine tuning in the operating frequency of the antenna.

2.7.1.2 1 x 2 Stacked Dual Polarized Dipole Antenna Sub-Array

A 1 x 2 dual polarized dipole antenna sub array is designed by stacking two layers of fundamental dual polarized dipole antenna. A L-bend is introduced in the top layer of the SICL feeding network to accommodate the feeding connectors between the simultaneously excited ports as shown in Fig. 2.25. The length of the bottom layer is incremented by the same additional length L_b of the L-bent as in top layer to maintain phase synchronization in the surface current exciting the dipole antennas in the two layers. To avoid generation of grating lobes in the radiated beam, the separation between the two layers supported by the plastic screws must be kept within the limit ($L_d < \lambda_g/2$) [Balanis, 2006].

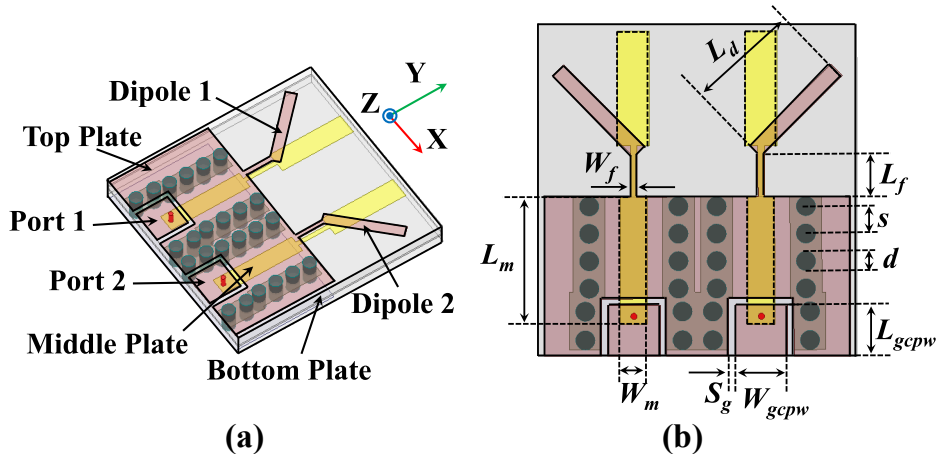


Figure 2.24: (a) 3D trimetric view and (b) top view of the proposed SICL fed dual polarized dipole antenna. Dimensions (in mm) : $L_d = 3.6$, $L_f = 1.8$, $W_f = 0.2$, $L_{gcpw} = 1.7$, $W_{gcpw} = 1.65$, $S_{gcpw} = 0.85$, $L_m = 4$, $W_m = 0.86$, $s = 0.9$, $d = 0.6$.

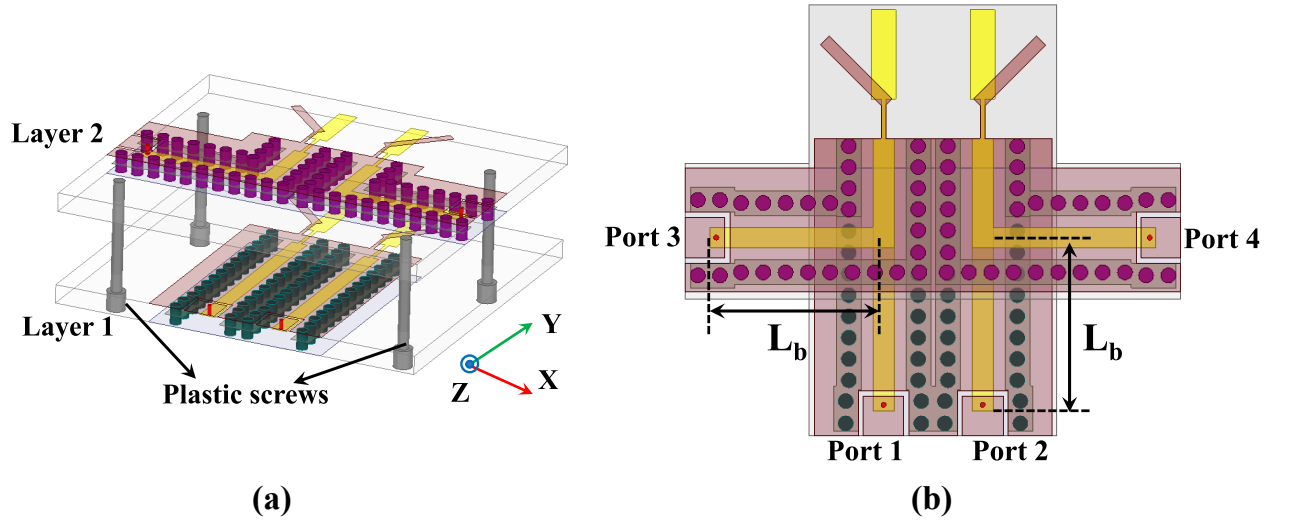


Figure 2.25: (a) 3D view and (b) top view of the proposed SICL fed 1 x 2 stacked dual polarized dipole antenna subarray.

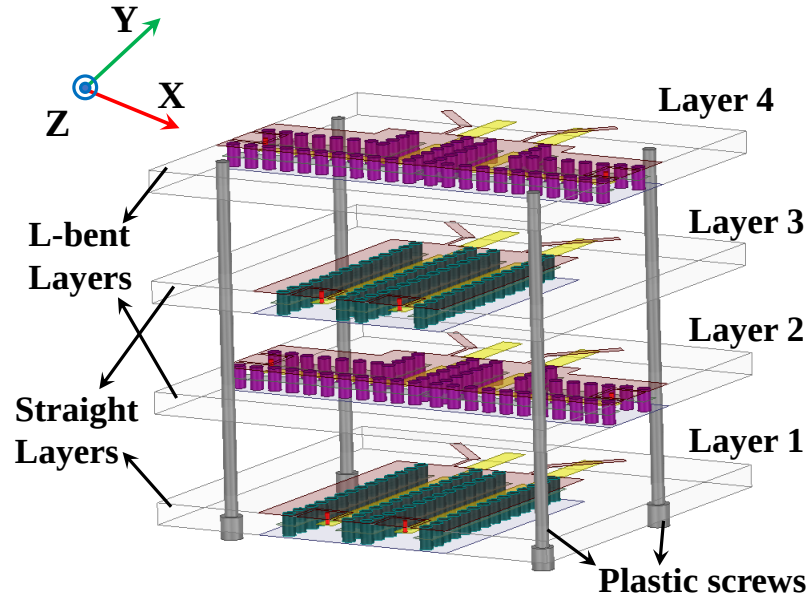


Figure 2.26: 3D trimetric view of the proposed SICL fed 1 x 4 stacked dual polarized dipole antenna array.

2.7.1.3 1 x 4 Stacked Dual Polarized Dipole Antenna Array

A 1 x 4 stacked dual polarized antenna array is designed by stacking two 1 x 2 dual polarized antenna sub-array as shown in Fig. 2.26. The antenna array thus formed consists of alternate layers of straight SICL feeding network and L-bent SICL feeding network. Four plastic screws through the substrate in each layer provides the support for the array. The length of the parallel feeding line L_f and dipole length L_d are optimized to obtain impedance matching for the proposed antenna array at the resonating frequency. The distance between the layers is tuned to obtain high gain while avoiding the generation of grating lobes. For optimum gain, the distance between the antenna layer is adjusted to 2.9 mm.

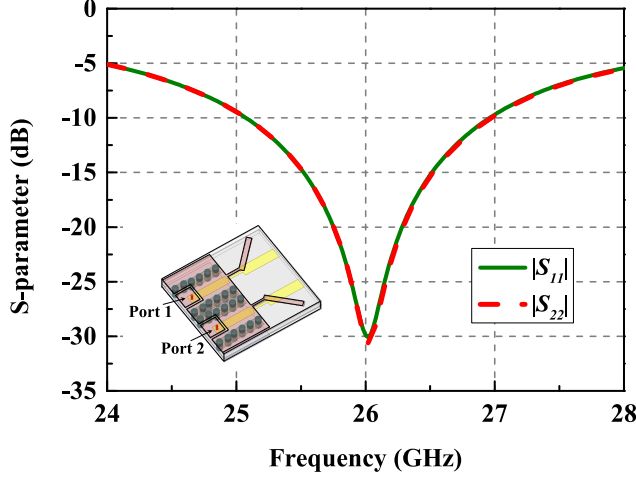


Figure 2.27: Reflection coefficient of the proposed SICL fed dual polarized dipole antenna.

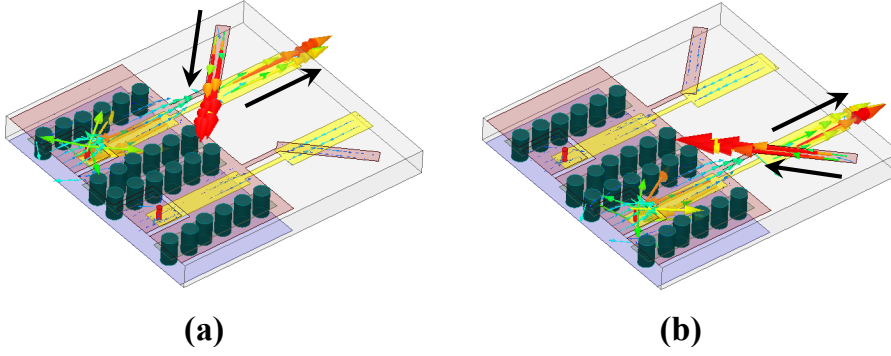


Figure 2.28: Surface current in top and middle conducting layer at 26 GHz for excitations in (a) port 1 and (c) port 2 for the proposed SICL fed dual polarized dipole antenna.

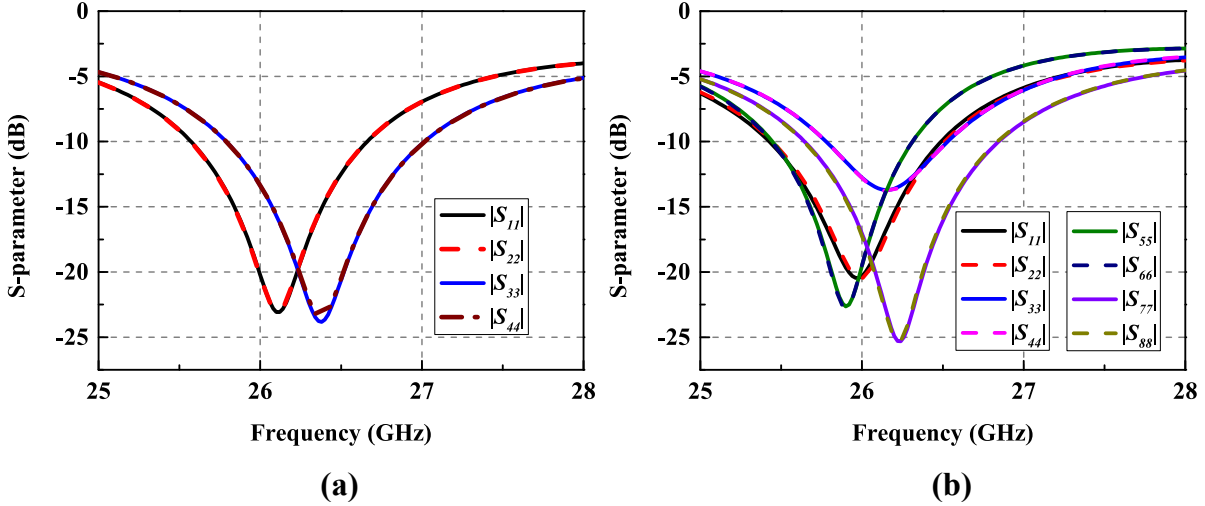


Figure 2.29: Reflection coefficient of the proposed SICL fed (a) 1 x 2 stacked dual polarized dipole antenna subarray and (b) 1 x 4 stacked dual polarized dipole antenna array.

2.7.2 Results and Discussion

The proposed dual polarized dipole antenna resonates at 26 GHz as shown in the reflection coefficient in Fig. 2.27. Dual polarization is controlled in the antenna by excitation of ports 1 and 2 feeding the two colocated orthogonal $\pm 45^\circ$ slant antennas. The surface current plotted in Fig. 2.28

Table 2.4: Performance for the Proposed 1 x 4 Dual Polarized Antenna Array

S. No.	Parameter	Dual Polarized Dipole Antenna	1x2 Stacked Antenna Subarray	1x4 Stacked Antenna Array
1.	Gain	3.36 dBi	4.03 dBi	7.6 dBi
2.	3-dB Beamwidth*	140.9°	108.9°	45.05°
3.	Cross-pol Ratio*	25.2 dB	21.96 dB	22.39 dB
4.	Front-to-Back Ratio*	7.1 dB	11.98 dB	12.13 dB

* Evaluated in H-plane beam.

depicts the excitation of dipole antennas alternately by port 1 and 2 respectively. The reflection coefficient of 1 x 2 dual polarized dipole antenna sub-array is shown in Fig. 2.29(a). There exists mutual coupling between the antennas of the top and bottom stacked layer which tends to shift in resonating frequency of dipole antennas slightly for the antennas excited simultaneously. The reflection coefficient of 1 x 4 dual polarized antenna array is shown in Fig. 2.29(b). Pronounced effect of mutual coupling in the two middle layers is evident from the reflection curve. The radiation pattern for the proposed dual polarized dipole antenna is plotted in E-plane ($\theta = 90^\circ$)/ H-plane ($\phi = +45^\circ$) for port 1 excitation and E-plane ($\theta = 90^\circ$)/ H-plane ($\phi = -45^\circ$) for port 2 excitation shown in Fig. 2.30. The top and bottom plate of the SICL feeding network acts as reflector for the backward travelling wave, thereby enhancing the front to back ratio (FTBR). Following the similar convention for E-plane and H-plane with odd and even numbered ports, the radiation pattern of the 1 x 2 stacked dual polarized dipole sub-array and 1 x 4 stacked dual polarized dipole antenna array

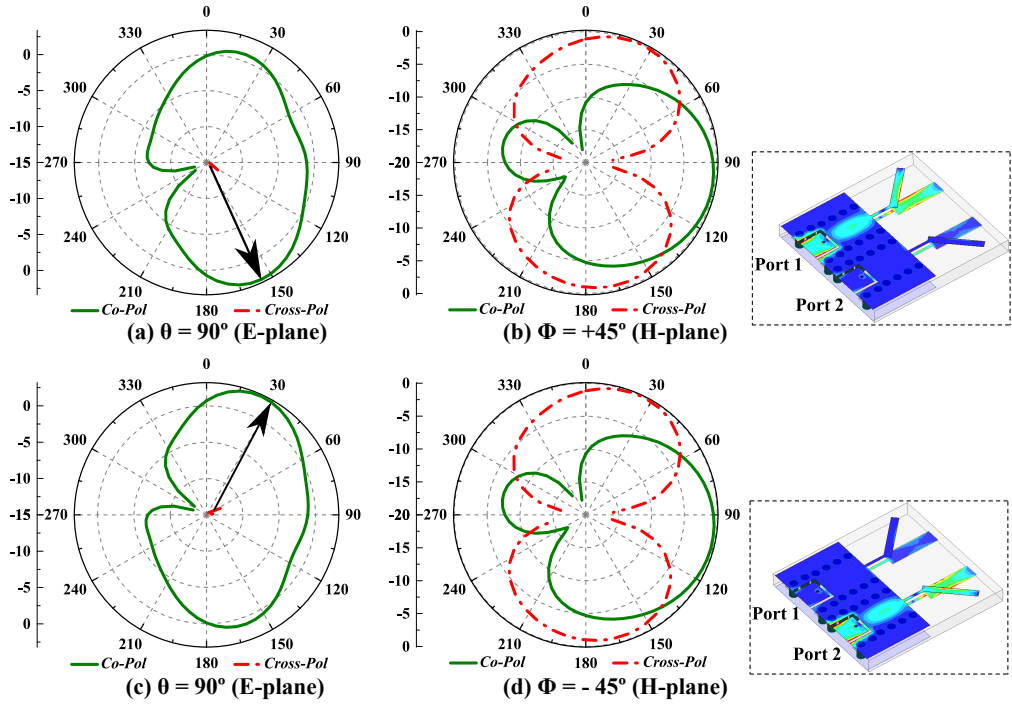


Figure 2.30: Radiation pattern and (inset) surface current on excited dipoles of the proposed SICL fed dual polarized dipole antenna at 26 GHz for excitation from (a),(b) port 1 and (c),(d) port 2 respectively. (Arrow pointing the maximum of beam in different directions)

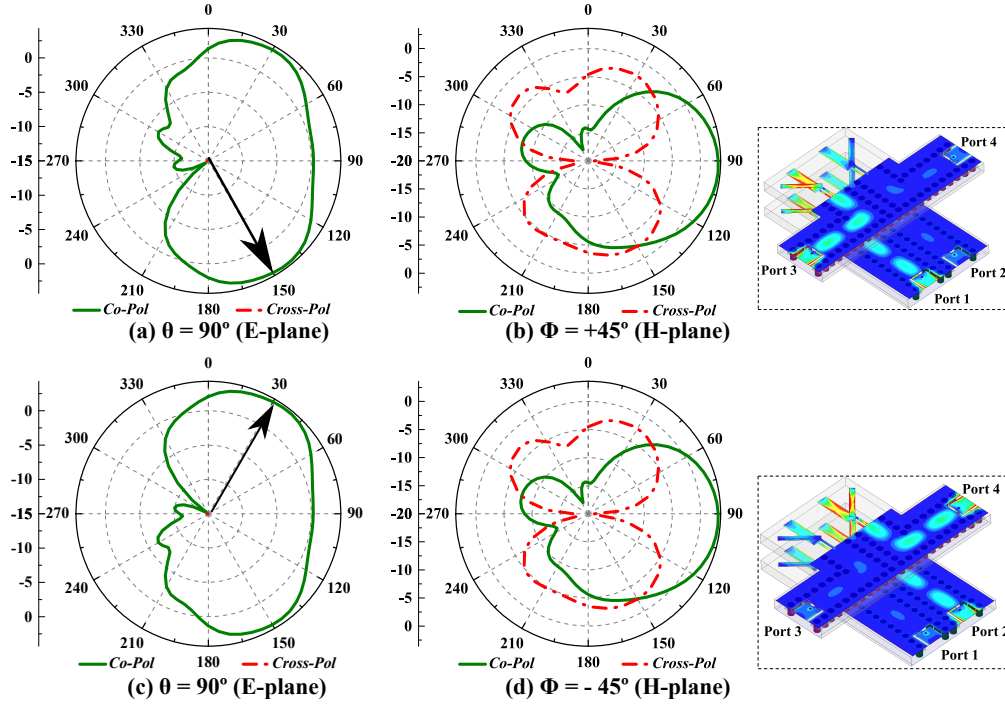


Figure 2.31: Radiation pattern and (inset) surface current on excited dipoles of the proposed SICL fed 1 x 2 stacked dual polarized dipole antenna subarray at 26.26 GHz for excitation from (a),(b) ports 1,3 and (c),(d) port 2,4 respectively. (Arrow pointing the maximum of beam in different directions)

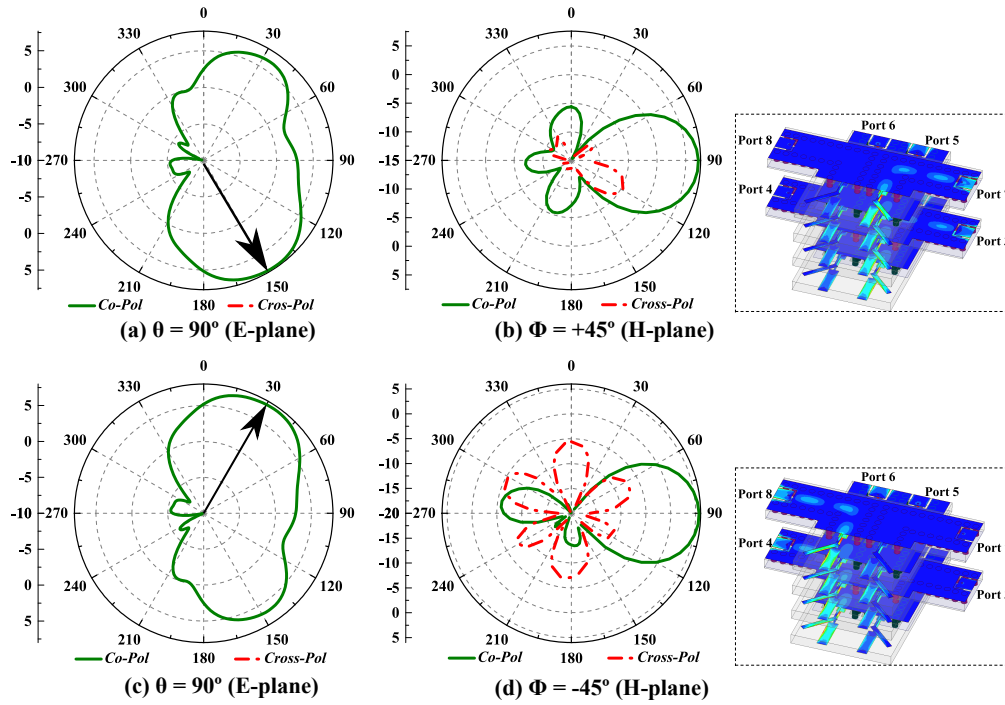


Figure 2.32: Radiation pattern and (inset) surface current on excited dipoles of the proposed SICL fed 1 x 4 stacked dual polarized dipole antenna array at 26.04 GHz for excitation from (a),(b) ports 1,3,5,7 and (c),(d) port 2,4,6,8 respectively. (Arrow pointing the maximum of beam in different directions)

is plotted in Fig. 2.31 and Fig. 2.32 respectively. Table 2.4 summarizes the performance of designed dual polarized antenna and its array. A fan-type beam in elementary antenna produces a broad

H-plane beam having 3-dB beamwidth of 140.9° . The beam of the array along the endfire direction becomes highly directive as observed by the decrease in the beamwidth to 45.05° . Simultaneously, the gain increases from 3.36 dBi of the elementary antenna to 7.6 dBi for the proposed array.

2.8 Design of Dual Frequency Dual Polarized Antenna Fed by Substrate Integrated Coaxial Line for 5G Millimeter Wave Application

This Section presents a novel dual-frequency antenna design in Substrate Integrated Coaxial Line (SICL) technology, which exhibits dual-polarization capabilities for 5G mm-wave application. A folded patch is designed using metallic post connected to both top and middle layer in the top substrate of SICL. The surface current and radiation patterns are analyzed to provide confirmation of both linear and circular polarization in the proposed antenna. To have broadside radiation, the bottom ground layer of the SICL is extended. The classical printed half-wavelength dipole antenna is designed at 28 GHz by feeding one dipole arm from the top layer and the other arm by the middle layer of the SICL. The novel antenna formed by the proposed co-located dipole and folded patch in this study exhibits a dual-frequency operation at 26.1 GHz and 29.85 GHz respectively. The designed antenna demonstrates linearly polarized unidirectional broadside beam with a gain of 6.5 dBi at first operating frequency 26.1 GHz and 3.2 dBic broadside LHCP gain at second operating frequency 28.95 GHz. This study showcases the efficacy of SICL in design of the proposed antenna and its feeding network, enabling simultaneous dual-frequency dual-polarized operation, rendering it well-suited for mmWave applications.

2.8.1 Design of Antenna

Substrate Integrated Coaxial Line (SICL) technology is implemented by two Taconic TLY-5A substrate (height of 0.5 mm each, $\epsilon_r = 2.2$) bonded together using Taconic FR-28 bond layer (height 0.1 mm, $2.75 < \epsilon_r < 2.9$) to design the proposed dipole antenna configurations [Baghel and Mukherjee, 2023]. A Grounded Co-Planar Waveguide (GCPW) to SICL transition is used to excite TEM based SICL transmission line [Baghel and Mukherjee, 2020a].

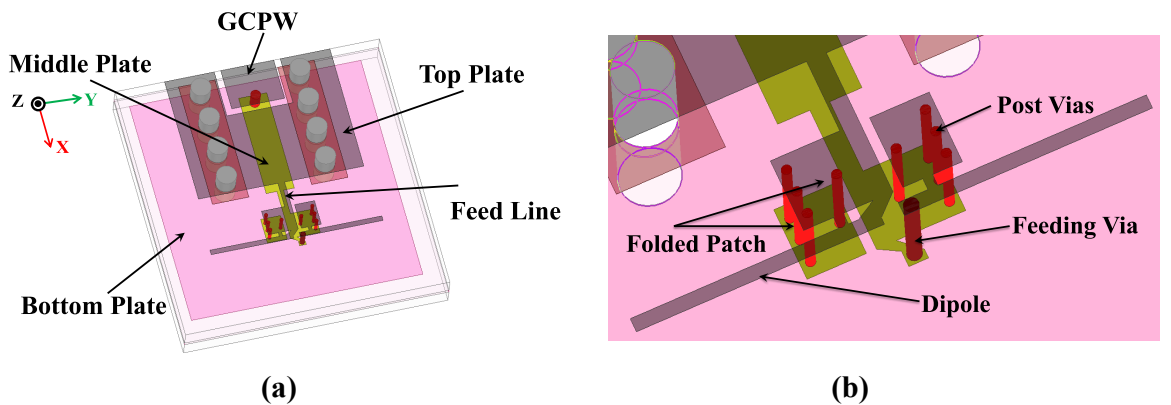


Figure 2.33: (a) Geometry and (b) enlarged view of proposed dual frequency dual polarized SICL fed antenna.

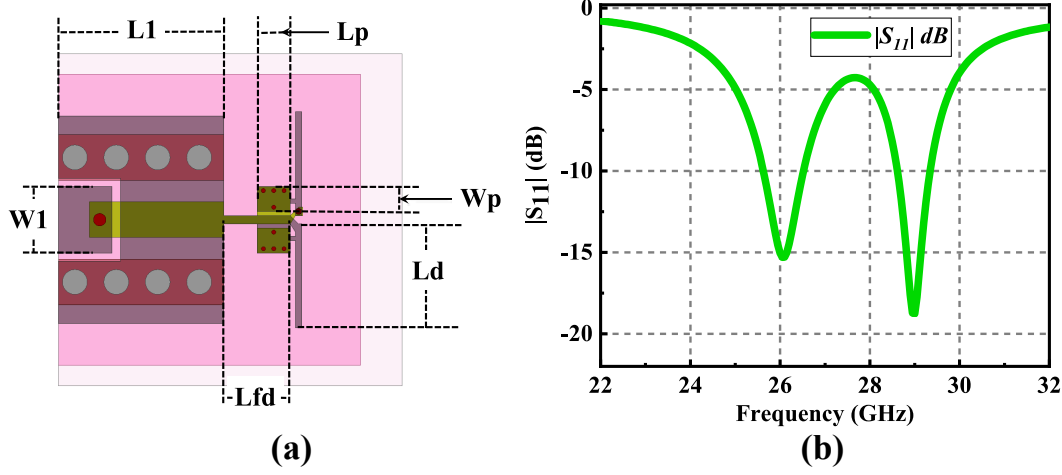


Figure 2.34: (a) Design dimensions and (b) reflection coefficient of proposed SICL fed dual-frequency dual-polarized dipole antenna.

Dimensions (in mm) : $W1 = 1.6$, $L1 = 4$, $Lfd = 1.6$, $Lp = 0.8$, $Wp = 0.8$, $Wp = 2.4$

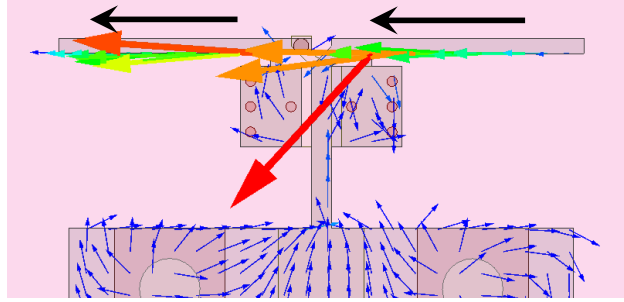


Figure 2.35: Surface current in the proposed SICL fed dipole antenna at 26.1 GHz.

2.8.1.1 SICL Fed Circular Polarized Folded Patch Antenna

To design the folded patch, an approximately half wavelength ($\lambda_g/2$) square patch antenna is designed in the top dielectric of the Substrate Integrated Coaxial Line (SICL). One half of the folded patch is connected to the top plate of SICL using a feed line and the other half of the folded patch is connected to the middle plate of SICL using post vias as shown in Fig. 2.33(a). Metallic Post are used to connect the top and middle patch to form folded patch antenna. The bottom plate of the SICL is extended below the folded patch to form an effective ground plane for broadside radiation.

2.8.1.2 SICL Fed Linearly Polarized Dipole Antenna

A conventional half wavelength ($\lambda_g/2$) dipole antenna is designed at 28 GHz in the top plate of the Substrate Integrated Coaxial Line (SICL). To feed the dipole antenna, two feed line are connected to the dipole arms. One arm of the dipole antenna is connected directly to the top plate of the SICL section. The other arm is connected to the middle plate of the SICL section using a small feed via as shown in Fig. 2.33(b).

2.8.2 Design of SICL fed Dual Frequency Dual Polarized Antenna

In order to form the dual frequency antenna with simultaneous dual polarization for the desired operating frequencies, a co-located configuration of the proposed SICL fed folded patch

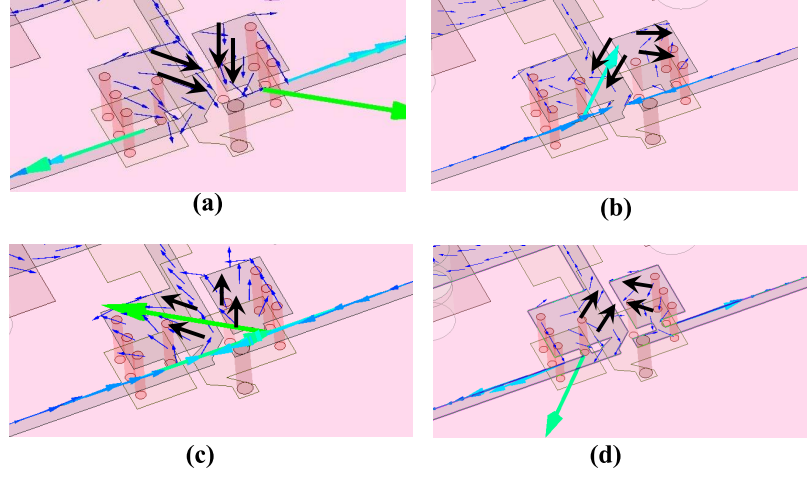


Figure 2.36: Surface current at time intervals (a) $t = 0$, (b) $t = T/4$, (c) $t = T/2$ and (d) $t = 3T/4$ in the proposed SICL fed folded patch antenna at 28.95 GHz.

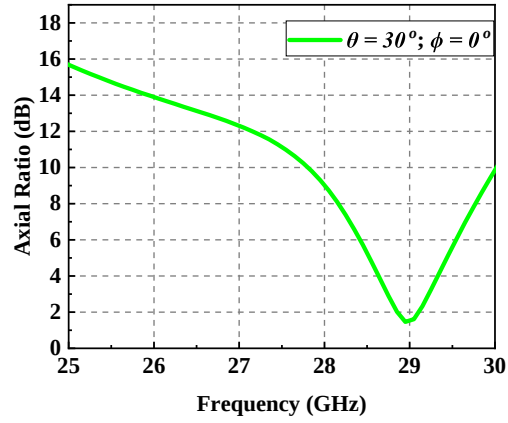


Figure 2.37: Axial ratio plot of the designed SICL fed dual-frequency dual-polarized antenna.

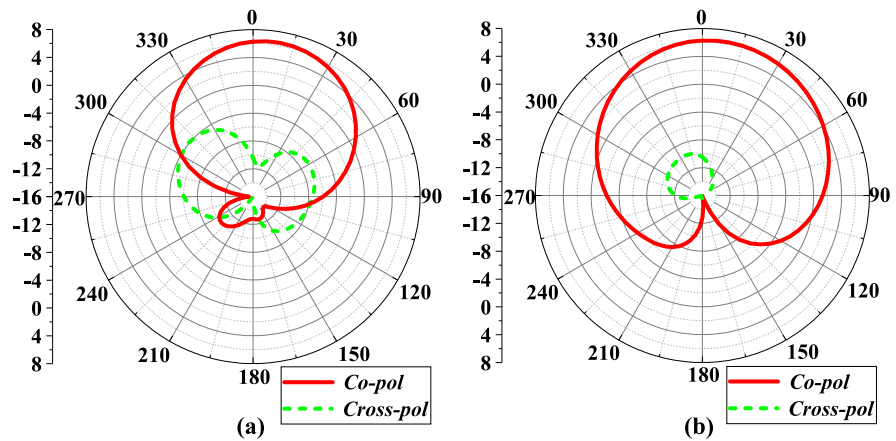


Figure 2.38: Radiation pattern in (a) $\phi = 0^\circ$ plane and (b) $\phi = 90^\circ$ plane of designed SICL fed antenna at 26.1 GHz.

antenna and SICL fed dipole antenna is implemented as shown in Fig. 2.33. The dipole antenna is kept ahead of the folded patch so that the fields in the dipole remains unaffected by the presence

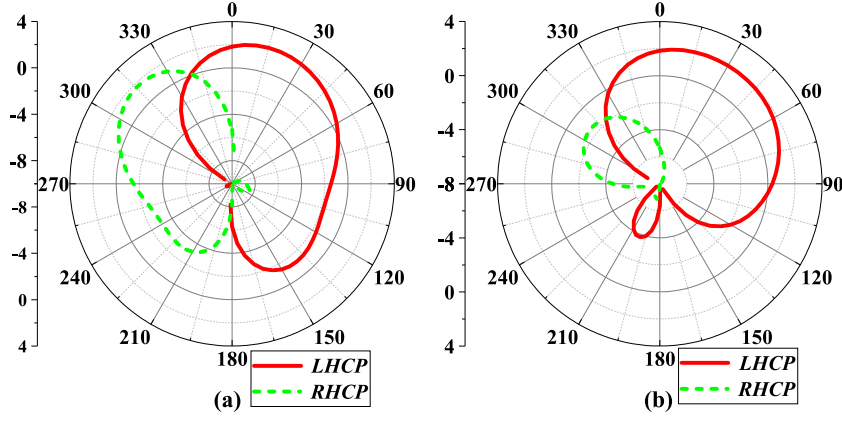


Figure 2.39: Radiation pattern in (a) $\phi = 0^\circ$ plane and (b) $\phi = 90^\circ$ plane of designed SICL fed antenna at 28.95 GHz.

of folded patch. The length of the dipole antenna is slightly tuned to compensate the loading effect from the folded patch. To improve -10 dB impedance matching for the folded dipole, small pads are introduced that connect the dipole arm to the folded dipole to load the patch antenna. The design parameters and dimensions of the proposed SICL fed dual frequency dual polarized antenna is given in Fig. 2.34(a).

2.8.3 Results and Discussion

The reflection coefficient is shown in Fig. 2.34(b) for the proposed co-located Substrate Integrated Coaxial Line (SICL) fed dual frequency dual polarized antenna. The designed SICL fed folded patch antenna resonates at 26.1 GHz exhibiting bandwidth of 900 MHz. SICL fed dipole antenna resonates at 28.95 GHz with a bandwidth of 750 MHz. The surface current distribution for the two antennas is shown in Fig. 2.35 and Fig. 2.36. The current in Fig. 2.35 depicts the excitation of the dipole antenna in the first operating band (26.1 GHz). The polarization achieved at the resonant frequency of the dipole is linearly horizontal polarized (H.P.). Fig. 2.36 shows the

Table 2.5: Comparison of reported dual polarized antennas with proposed work

Work	Antenna	Frequency	Polarization	Remarks
[Zou <i>et al.</i> , 2023]	Periodic circular grid patch	3.5/ 28 GHz	Dual linear	• Non-planar • Multi-port feed network • Millimeter wave frequency
[Feng and Leung, 2016]	Folded parallel plate & Waveguide resonator antenna	2.45/ 24.15 GHz	Circular	• Non-planar • Complex feeding with L-probe • Microwave/ millimeter wave frequency
[Bao and Ammann, 2011b]	Dipole	2.7/ 7 GHz	Circular/ Linear	• Non-planar • Multi-port feed network • Microwave frequency
[Liu <i>et al.</i> , 2020]	Microstrip patch	2.1/ 2.2 GHz	LHCP/ RHCP	• Low efficiency • Microwave frequency
[Bao and Ammann, 2011a]	Spiral slot	1.6/ 2.6 GHz	LHCP/ RHCP	• Unshielded microstrip feed • Microwave frequency
This work	Dipole integrated with Folded patch	26.1/ 28.9 GHz	Linear/ Circular	• Planar • Single-port design • Millimeter wave frequency

rotational surface current at different time intervals depicting circular polarization. The circular polarization achieved at the second resonating frequency is from the combination of fields from the dipole and the folded patch. The linearly polarized dipole (H.P: horizontal polarization along Y) and the linearly polarized patch (V.P: vertical polarization along X), results in circular polarization at the second resonant frequency. The axial ratio plot for circular polarization is shown in Fig. 2.37, which clearly depicts the axial ratio below 3 dB at second operating frequency. The bottom plate of the SICL acts as the back reflector for the backward radiation. These back radiations interfere constructively with forward radiation and thereby increases the gain of the antenna and provides improvement in Front-to-Back Ratio (FTBR). The radiation pattern for the SICL fed dipole antenna is plotted in Fig. 2.38 in the E- and H-plane at 26.1 GHz. The dipole antenna exhibits high FTBR of 18.9 dB and high cross-polarization level of 16.6 dB. Fig. 2.39 shows the radiation pattern of the SICL fed folded patch antenna at 28.95 GHz. The folded patch antenna exhibits FTBR of 6 dB and cross-polarization level of 6.5 dB. Table 2.5 presents the comparison of the proposed work with the reported literatures. Different from the common approaches of obtaining dual polarizations by multiple ports for dual polarized antennas, or utilizing a complex feed network such as L-probe in non-planar 3D antennas. The presented work presents a single port antenna design with subsequent linear and circular polarization in a compact footprint.

2.9 Conclusions

This chapter discusses the design and principle of operation for SICL fed antennas. We have proposed few SICL based dipole antenna designs with different approaches to enhance the bandwidth for 5G millimeter wave frequencies. Firstly, the design of a broadband dipole antenna excited using SICL feed network. SICL emerges as the technology that overcomes the barriers in SIW technology by providing a unimodal TEM mode propagation that has been efficiently utilized to design a broadband dipole antenna. A parasitic dipole antenna kept close to the primary antenna, gets coupled to the antenna and radiates. This approach improves the gain and bandwidth of the antenna. Later, SICL fed quasi-Yagi antenna has been proposed and the demonstrated results encourages its utilization at millimeter wave frequencies. The truncated upper conductor plate acts as reflector and thereby improves the antenna characteristics. With spurious radiation in microstrip feed and radiation, conduction losses in coplanar waveguide, these techniques have low efficiency at millimetre wave frequencies. Having stated the benefits of using SICL, the proposed antenna shows improvement in gain compared to the other works. Next work considers the design of a Bow-Tie antenna in SICL substrate. The SICL excited Bow-Tie antenna is designed to obtain wideband performance. SICL technology having the advantage of wideband TEM mode of operation, provides an efficient feeding network. This performance of the antenna shows that it can be employed for different broadband mmwave applications, as it covers all the bands allocated at 24 GHz and 28 GHz for 5G application within different countries.

The second part of the chapter discusses three different dual polarized antennas. Three different design techniques are proposed to obtain polarization diversity in SICL fed endfire and broadside dipole antennas. Firstly, a dual polarized antenna is obtained using orthogonal antenna on either side of the SICL substrate. Dual linear polarization is achieved in this design by controlling the excitation of the two antennas using RF switch. Two diodes are placed on the two feedlines connecting the two dipoles on the top and bottom plate with the SICL feed section. This antenna exhibit endfire radiations with a gain of 4.9 dBi and wide 31% bandwidth with high cross-polarization better than 20 dB. Second dual polarized antenna proposed in this chapter, produces polarization diversity by controlling the excitation of the two dipole antennas placed on the same side of the substrate. An endfire array of the proposed antenna is designed by stacking 4 layers of the proposed antenna configuration. L-bend is introduced in the SICL feed structure to accommodate 50 Ω end-launchers in successive layers for exciting the antennas. The proposed 1 x 4 stacked

antenna array exhibit a gain of 7.6 dBi with high cross-polarization ratio of 22.39 dB with FTBR of 12.13 dB. Lastly, we observe a dual polarization in a dual-frequency antenna designed using a dipole antenna and folded patch antenna fed by the same SICL feed section. The bottom ground plate of the SICL below the antennas is extended to obtain broadside beam. The placement of the folded patch and dipole antenna results in linear polarization (L.P.) at 26.1 GHz and circular polarization (LHCP) at 28.9 GHz.

The out of phase surface current between the top/bottom and middle layer of SICL, makes the way for this technology to be used for feeding planar antennas. This out-of-phase surface current is efficiently utilized to feed the two arms of the dipole antenna and thereby SICL removes the need to have balun (balanced to unbalanced transformer) in the feeding network, making the design compact. Interestingly, the top and bottom layer of the SICL feeding section acts as the back reflector that reflects back the back lobe and improves Front-to-Back ratio (FTBR) of the radiated beam. Self-shielded structure contributes in achieving high isolation required in dual polarization applications. Results of the proposed antenna designs using SICL show low cross-polarization ratio. Thus, SICL serves as an effective feeding technology to serve the demands of dual polarized antennas and combats the challenges in designing efficient dual polarized antennas for 5G mmwave applications.

The study presented in this chapter shows that the broadband dipole antenna achieves a bandwidth of 5.5 GHz, while Quasi-Yagi antenna exhibits a comparable bandwidth performance of 6.3 GHz. The Bow-Tie antenna on the other hand gives much higher bandwidth of 8.7 GHz. Three different configurations of the dual polarized antennas have been proposed in the FR2 mm-wave band where controlling the polarization is performed using diode and port excitations. The performance of the proposed antenna designs encourages its applications where design dimension and high gain are the critical demands for modern wireless communication systems.