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RESEARCH ARTICLE

A Novel Half Mode SICL Based Dual Beam Antenna Array for Ka-Band Application

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ABSTRACT In this paper, we propose a novel Half Mode Substrate Integrated Coaxial Line (HMSICL) cavity fed monopole antenna at 28 GHz. A SICL cavity is bisected along its symmetric magnetic wall (PMC) to create an open-ended Half Mode SICL (HMSICL) cavity. The proposed HMSICL cavity is used to excite a tapered monopole antenna to radiate in endfire direction with a gain of 6.4 dBi at 28 GHz. For dual beam application, it is integrated with unidirectional broadside Half Mode Substrate Integrated Waveguide (HMSIW) antenna exhibiting a gain of 5.1 dBi that provides spatial diversity to the proposed design. To achieve high gain, two co-located 1×4 linear HMSICL and HMSIW array are placed side-by-side such that the proposed design produces simultaneous endfire and broadside beams for In-Band Full Duplex (IBFD) applications. The proposed passive Signal Interference Cancellation (SIC) technique is utilized to minimize the overlap of simultaneous dual beam at 28 GHz by orienting the two antennas within a compact footprint. The full duplex antenna array achieves a gain of 10.8 dBi in endfire and 10.3 dBi in broadside direction with high isolation below 45 dB over 500 MHz bandwidth. The presented antenna array is a potential candidate for relay where the transmitting and receiving signals are in two different directions.

INDEX TERMS Half mode SICL (HMSICL), half mode SIW (HMSIW), high isolation.

I. INTRODUCTION

Channel sharing and spectrum re-use is becoming popular to improve spectral efficiency for faster communication in recent years. Researchers and antenna engineers around the world are trying to design and develop antennas that have potential to exploit the bandwidth completely by simultaneous transmission and reception in a single frequency spectrum from a node. Thus, dual beam antennas equipped with spatial diversity are in high demand for their excellent polarization properties and wide field of view capability.

Such dual beam antennas find application in several scenarios as depicted in Fig. 1. A Device-to-Device communication between two end-users require simultaneous transmission and reception through a relay at base stations. Communication in urban cities is possible through an efficient multi-hop link between Non-Line-of-Sight (NLOS) end-users. Relays with simultaneous dual beam establish a communication link between two end users for NLOS communication [1] as shown in Fig. 1. An In-Band Full Duplex (IBFD) antenna array used in streetlight deployment and over building is the upcoming easy cost-effective solution for deployment in Ka-band for faster Vehicle-to-Vehicle communication. However, IBFD antennas have been regarded impractical in the past due to the strong Self Interference (SI). Several active and passive suppression techniques such as passive suppression through antenna isolation, active suppression via analog and digital cancellation [2] have been proposed to compensate for self interference. The basic passive suppression technique is the physical separation of the

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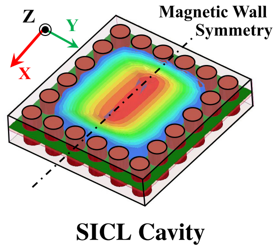
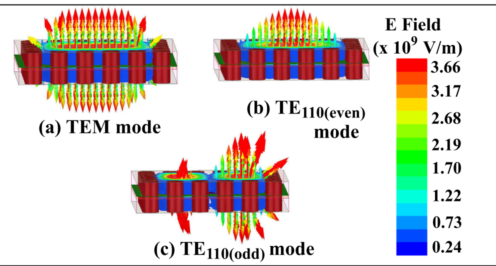
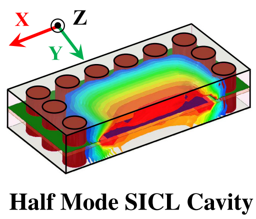
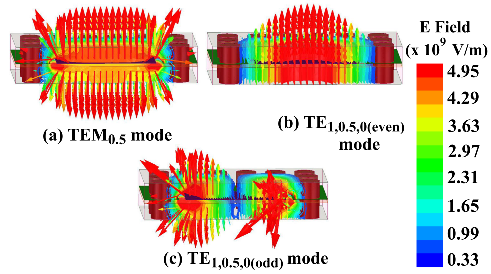
TABLE 1. Development of Half Mode SICL cavity.

S.No.	Cavity type	Resonant modes in the cavity
1.		
2.		

– SICL cavity modes: TEM @ 28 GHz; $TE_{110(even)}$ @ 37 GHz; $TE_{110(odd)}$ @ 39GHz
– HMSICL cavity modes: $TEM_{0.5}$ @ 28 GHz; $TE_{1,0.5,0(even)}$ @ 37 GHz; $TE_{1,0.5,0(odd)}$ @ 39GHz

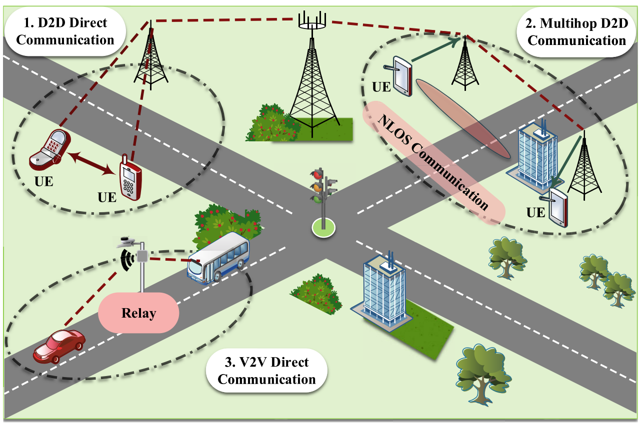


FIGURE 1. Illustration of a various spatial diversity scenarios in a wireless communication network.

antenna where the propagation loss of the wave is exploited to achieve isolation between two colocated antennas [3], [4]. These techniques provide an isolation typically of the order of 20 - 30 dB [5]. Other passive SIC techniques such as coupling network, absorbers, reflective surface, couplers and circulators involve additional passive element and lumped elements that makes the antenna design bulky and increases the effective footprint of the antenna. In [6], one such Radar system has been proposed that comprises of coupler in up-conversion and down-conversion stages along side Low Noise Amplifier (LNA) to achieve isolation between the transmitted and received signal.

The Substrate Integrated Coaxial Line (SICL), first introduced by Gatti et al. [7], is a three-conductor transmission line that implements the rectangular Coaxial Line in planar substrates. The electromagnetic field in SICL line resembles the TEM mode propagation in conventional coaxial line [8]. The middle conducting plate is sandwiched between the top & bottom plate and is encapsulated between two rows of vias on either side that provides it effective shielding. Recently several research works on antenna and circuit design in the novel Substrate Integrated Coaxial Line (SICL) technology for 5G applications have been proposed by several research groups across the world. Millimeter wave SICL transitions [9], [10], compact half mode cavity resonator based filter [11] have been reported. 28 GHz SICL based cavity backed slot antenna and dual band operation at 28/ 38 GHz has been studied in [8] and [12]. Dual polarized SICL fed dipole antennas at 28 GHz have been explored in [13] and [14]. Further crossed dipole configurations for dual band operation at 26/ 28 GHz and MIMO operation at 28 GHz have been proposed for SICL in [15] and [16]. Studies on SICL based slot antenna arrays at mmWave frequencies to generate unidirectional [17] and bidirectional [18] beams are also reported. In this paper, we propose a simple passive approach to design an In-Band Full Duplex (IBFD) antenna using novel HMSICL cavity fed monopole antenna at 28 GHz. The contribution of the work is described below:

- To the best of author's knowledge, this work presents the first half mode Substrate Integrated Coaxial Line (SICL) fed antenna design.
- The novelty lies in designing Half Mode Substrate Integrated Coaxial Line (HMSICL) based antenna and its integration with Half Mode Substrate Integrated Waveguide (HMSIW) antenna for full-duplex application.
- The proposed work utilizes novel HMSICL and HMSIW cavity antennas for In-Band Full Duplex performance

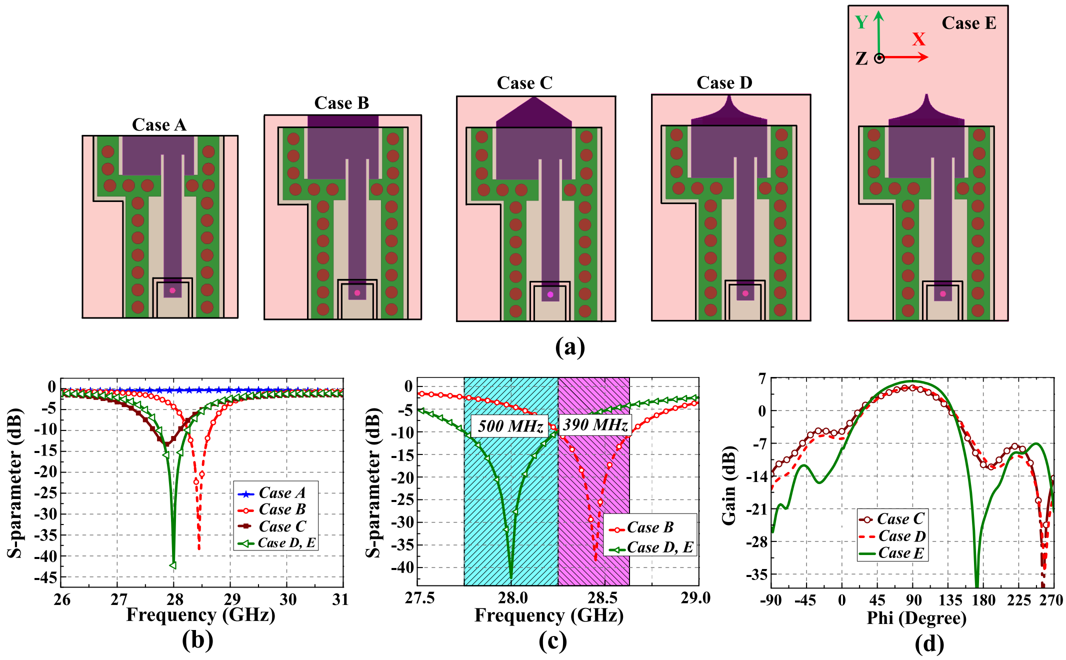


FIGURE 2. (a) Evolution of the proposed novel Half Mode SICL (HMSICL) cavity fed monopole antenna. Comparative study in (b) reflection coefficient, (c) bandwidth improvement and (d) gain pattern at 28 GHz, to obtain the proposed HMSICL cavity fed monopole antenna design (endfire direction along $\phi = 90°$).

at 28 GHz making time division duplex (TDD) operation realizable for both Simultaneously Transmit and Receive (STAR) operation.

- The proposed work utilizes the simplest technique for Signal Interference Cancellation (SIC) that removes the need of additional passive/ lumped elements thereby making the design compact.

In this work, high isolation of 45 dB at the primary antenna stage reduces the load over the analog and digital cancellation stages and thereby inhibits saturation condition of the system.

II. DESIGN

The proposed design of Full Duplex antenna consists of two half mode (HM) antennas in two distinct planar technologies namely, Substrate Integrated Coaxial Line (SICL) and Substrate Integrated Waveguide (SIW). A pre-preg layer FR-28 (height 0.1 mm, 2.75< ϵ_r <2.9) is used to bond two Taconic TLY-5A substrates (height of 0.5 mm each, $\epsilon_r = 2.2$) to design the proposed antenna. A 28 GHz Substrate Integrated Coaxial Line (SICL) cavity is designed by enclosing the two edges of the SICL transmission line by PEC boundary and keeping the other two edges open ended to form PMC boundary [8] as shown in Table 1.

A. DEVELOPMENT OF HMSICL CAVITY

The metallic vias around the periphery of the cavity provides a perfect electric wall boundary (PEC). As seen from the field distribution, magnetic wall symmetry plane (PMC) is present at the center of the cavity. A Half Mode Substrate Integrated Coaxial Line (HMSICL) cavity is formed by bisecting the SICL cavity along the symmetric PMC boundary [11], [19]. The truncated HMSICL cavity is exactly half the dimension of the SICL cavity. The proposed HMSICL cavity is investigated using eigen mode analysis. Table 1 shows the development of HMSICL cavity from SICL cavity with the resonant modes explained through electric field distribution in the cavity.

The first resonant mode in the SICL cavity is the TEM mode occurring at 28 GHz. The next two higher order modes following the TEM mode are orthogonal, $TE_{110(even)}$ and $TE_{110(odd)}$ mode at 37 GHz and 39 GHz frequency respectively. Further as the SICL cavity is bisected from the center, HMSICL cavity has its first half mode, $TEM_{0.5}$ occurring at 28 GHz. The next two higher order half modes are orthogonal modes namely, $TE_{1,0.5,0(even)}$ and $TE_{1,0.5,0(odd)}$ occurring at 37 GHz and 39 GHz respectively. It is observed that the frequencies at which the resonant modes occur in the SICL and HMSICL cavity does not change. It is due to the fact that the height of the open-ended half mode cavity is small making the open-ended aperture nearly perfect open in nature. Hence, perturbation in the field is small at the open-ended face.

B. HALF MODE SICL CAVITY FED MONOPOLE ANTENNA

The proposed Half Mode Substrate Integrated Coaxial Line (HMSICL) cavity exhibits good potential for endfire radiation from its open-ended aperture. A Grounded Co-Planar Waveguide (GCPW) to SICL transition is used to feed the cavity [8]. To facilitate radiation, step-by-step design procedure is adopted as shown in Fig. 2.

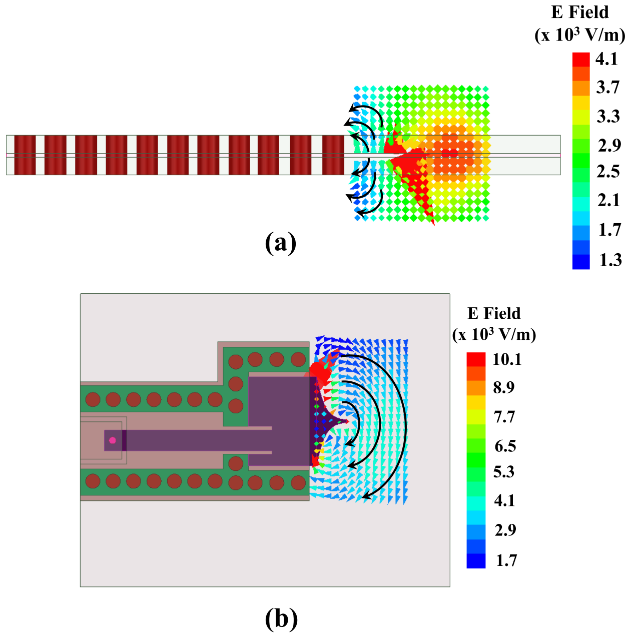


FIGURE 3. Electric field distribution along the monopole antenna in (a) side view and (b) top view of the proposed half mode SICL (HMSICL) cavity fed monopole antenna.

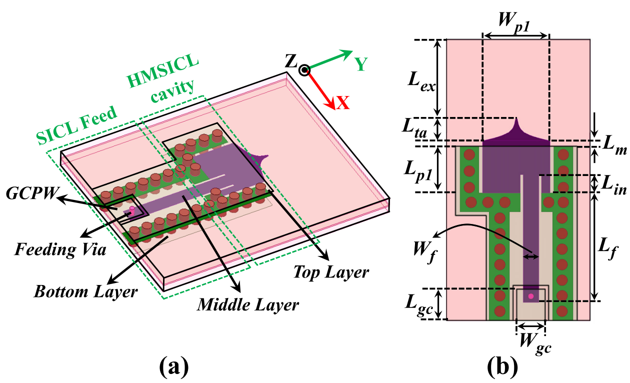


FIGURE 4. (a) Isometric view and (b) top view of the proposed half mode SICL cavity fed monopole antenna. The dimensions are (in mm): ***L_{ex} = 4.3, L_{ta} = 1.25, L_{p1} = 2.55, W_f = 0.85, L_{gc} = 1.7, W_{gc} = 1.54, L_f = 6, L_{in} =1, L_m = 0.3, W_{p1} =3.7.***

The fringing field in the proposed truncated Half Mode SICL (HMSICL) cavity radiates from its open-ended aperture as depicted by *Case A* in Fig. 2(a). Since the height of the substrate is small, the size of the aperture is less. This results in impedance mismatch and as a result, negligible radiation is observed in *Case A*. Next, the half mode cavity middle layer is increased slightly as in *Case B*. Extension of the middle layer helps in impedance matching as well as behaving as a monopole radiator resonating at 28.45 GHz as shown in Fig. 2(b) with a fair gain of 3 dBi. The bandwidth of the antenna in this design is 390 MHz. Further to improve the impedance matching of the antenna with the free space impedance, the middle layer of the antenna is further extended towards the endfire direction. Different tapering of the monopole antenna radiating aperture are investigated

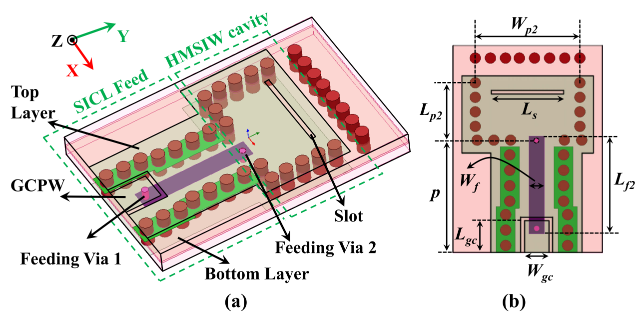


FIGURE 5. (a) Isometric view and (b) top view of the proposed Half Mode SIW (HMSIW) cavity backed slot antenna. The dimensions are (in mm): ***L_{p2} = 3.1, W_{p2} = 5.7, L_{gc} = 1.75, W_{gc} = 1.55, L_{f2} = 5.38, L_s = 4.0, p = 6.12.***

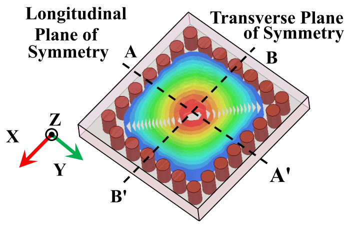
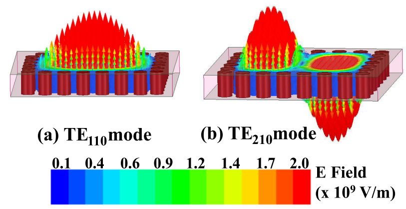
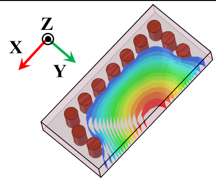
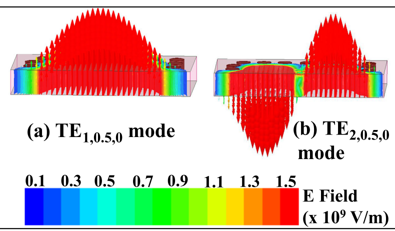
to simultaneously provide good gain with broad bandwidth. A triangular antenna fed by middle layer as in *Case C* shifts the resonance to 27.87 GHz. Due to the better impedance matching, the bandwidth of the antenna increases to 450 MHz and good gain of 4.8 dBi is obtained. Further, by utilizing exponential tapering as shown in *Case D*, the antenna achieves additional impedance matching and it resonates at the desired 28 GHz frequency. Thereby, in effect, the bandwidth of the antenna is increased to 500 MHz in *Case D* as depicted in Fig. 2(c). The gain achieved in this case is 5 dBi and the pattern has a broad beamwidth. In order to design antenna array with suppressed sidelobe level, it is expected to have narrow beamwidth for the antenna. Thereby increasing the substrate along the endfire direction as in *Case E*, results in reducing the beamwidth of the antenna and simultaneously an increased gain of 6.4 dBi at 28 GHz is obtained for the proposed HMSICL cavity fed monopole antenna as shown in Fig. 2(d). Electric field distribution along the monopole radiator as shown in Fig. 3 shows TEM field excitation from the proposed HMSICL cavity to the monopole antenna.

The final design of novel Half Mode Substrate Integrated Coaxial Line (HMSICL) cavity fed monopole antenna is shown in Fig. 4. The dimension of HMSICL cavity L_{p1} is chosen nearly half of SICL cavity [8] and monopole radiator ($L_{ta} + L_m$) is kept nearly quarter-wavelength ($\lambda_g/4$) to have resonance at the desired frequency of operation. To accommodate an end-launcher, the length of the feed line L_f is kept 6 mm. The feed line is offset from the center position by 0.8 mm and is inset by L_{in} in the HM cavity to have proper impedance match at the operating frequency. The dimensions of the middle patch W_{p1} and L_{p1} is optimized to have the resonance at 28 GHz. The design dimensions of the proposed HMSICL fed monopole antenna is given in Fig. 4(b).

C. HALF MODE SIW ANTENNA

A 28 GHz Substrate Integrated Waveguide (SIW) cavity is designed by enclosing the substrate by via-wall on all sides [20]. Half mode SIW (HMSIW) antenna is formed by bisecting the SIW cavity along the symmetric perfect magnetic (PMC) boundary [21], [22]. The HMSIW cavity along with its modes are depicted in Table 2. The proposed

TABLE 2. Development of Half Mode SIW cavity.

S.No.	Cavity type	Resonant modes in the cavity
1.	 SIW Cavity	
2.	 Half Mode SIW Cavity	

– SIW cavity modes: TE_{110} @ 28 GHz; TE_{210} @ 41.5 GHz

– HMSICL cavity modes: $TE_{1,0.5,0}$ @ 28 GHz; $TE_{2,0.5,0}$ @ 43 GHz

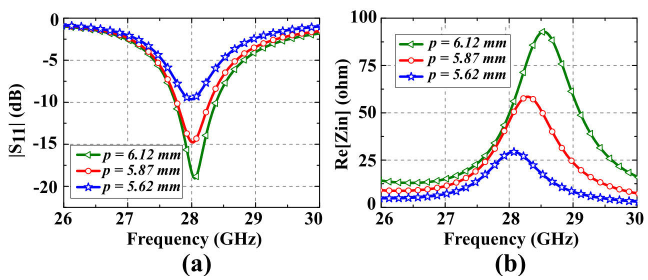


FIGURE 6. Variation in (a) reflection coefficient and (b) input impedance with the position of SIW *FeedingVia*2 (*p*) in the proposed HMSIW antenna.

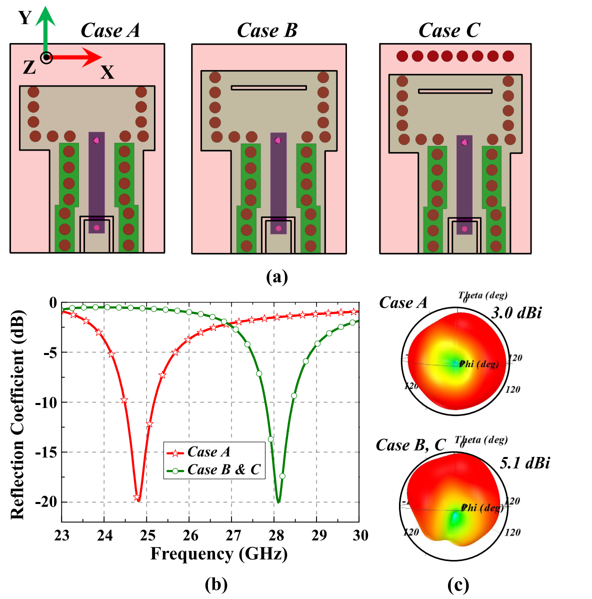


FIGURE 7. (a) Evolution of proposed HMSIW cavity antenna. Comparative study in (b) reflection coefficient and (c) gain of the proposed HMSIW cavity antenna.

HMSIW cavity antenna is shown in Fig. 5 and its detailed analysis is explained below. The dimensions of the HMSIW cavity and the slot radiator L_{p2} and L_s respectively, is chosen approximately half-wavelength ($\lambda_g/2$) to have resonance at the desired frequency of operation. The design of the HMSIW cavity starts with exciting the HMSIW cavity with the SICL feed line. A 50 Ω GCPW-to-SICL transition is used to excite the SICL transmission line. To excite the HMSIW antenna, *FeedingVia*2 connecting the middle layer of the SICL feed line to the bottom layer of the HMSIW cavity is used. The position of the feeding via (p) impacts the matching of the antenna as shown in Fig. 6. The input impedance in Fig. 6(b) is obtained by de-embedding the feed line in Ansys HFSS simulation tool. The SICL feed line is offset from the center to have a optimum impedance match.

The designing steps of the proposed HMSIW antenna is explained in Fig. 7. The HMSIW cavity antenna as shown in *Case A* has the resonance at 24.75 GHz as shown in Fig. 7(b) and radiates a near-omnidirectional beam with a gain of 3 dBi as depicted in Fig. 7(c). The effective length of the half mode SIW is increased due to the fringing field which shifts resonant frequency to the lower side. To have resonance at the desired operating frequency 28 GHz, the cavity top & bottom layers are slightly increased as in *Case B*. In order to have unidirectional radiation, a slot is etched on the top layer of the HMSIW cavity as depicted in *Case B* to form the proposed antenna. Thereby the gain of the antenna is increased to 5 dBi and a broadside unidirectional radiation is obtained as shown in Fig. 7(c). In order to avoid leakage of surface wave in the endfire direction, via-wall is placed along the open-ended edge of the HMSIW cavity as depicted in *Case C*.

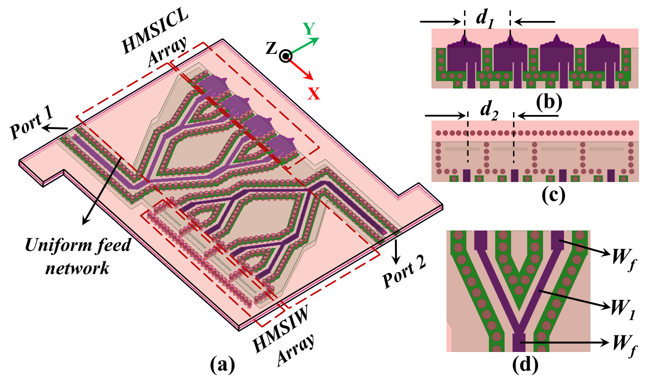


FIGURE 8. (a) Geometry of the proposed dual beam antenna array in isometric view. 1 × 4 linear array of (b) half mode SICL and (c) half mode SIW. (d) A section of feeding network depicted dimensions (in mm): $W_f = 0.85$, $W_1 = 0.5$.

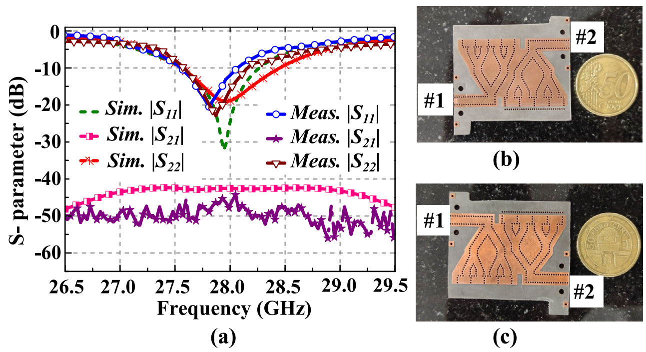


FIGURE 9. (a) Reflection coefficient, (b) top view and (c) bottom view of the proposed dual beam antenna array.

D. DUAL BEAM ANTENNA ARRAY

To validate the Simultaneous Transmit and Receive (STAR) operation at the same frequency, an In-Band Full Duplex (IBFD) antenna array is designed by using the proposed Half Mode Substrate Integrated Coaxial Line (HMSICL) cavity fed monopole antenna and Half Mode Substrate Integrated Waveguide (HMSIW) cavity based antenna as shown in Fig. 8. An uniform array of HMSICL antenna and HMSIW antenna is formed by placing the antenna elements side-by-side sharing the common via-wall, thereby making the array compact. A two stage Y-junction equal power divider is used to implement a four way feeding network for the array. The design dimensions of the feeding network is given in Fig. 8. The width W_f is chosen to achieve 50 Ω characteristic impedance of the SICL line, which enables easy integration of the power divider with the antenna elements. The line width W_1 in the Y-junction of the power divider implements the 70.7 Ω SICL section to facilitate equal power division at the output ports.

A 1 × 4 linear array of the HMSICL and HMSIW cavity based antenna are oriented in opposite direction to provide separation between the antennas. The two antenna arrays are placed in closed proximity to minimize the physical footprint. To avoid generation of grating lobes, the separation between elements in an HMSICL endfire array and HMSIW broadside array is d_1 is 5.1 mm ($< \lambda_0/2 = 5.3$ mm) and d_2 is 5.7 mm ($< \lambda_0 = 10.7$ mm) respectively.

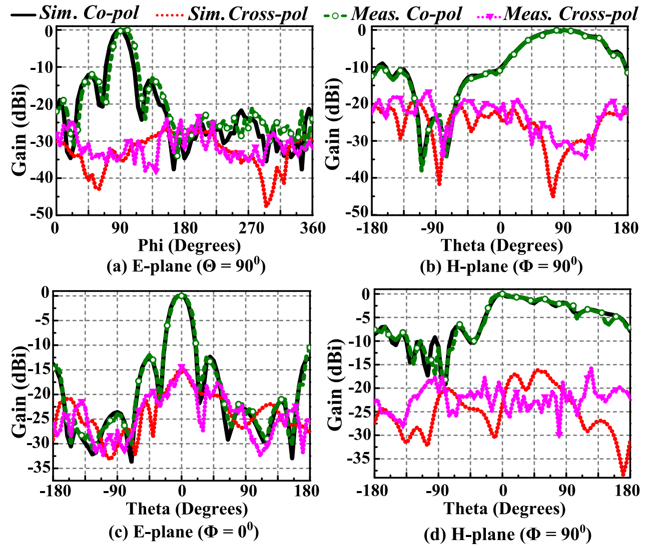


FIGURE 10. Radiation pattern in (a) E-plane ($\theta = 90°$), (b) H-plane ($\phi = 0°$) for port 1 excitation of HMSICL cavity fed monopole antenna, (c) E-plane ($\phi = 0°$) and (d) H-plane ($\phi = 90°$) for port 2 excitation of HMSIW cavity backed antenna of the proposed dual beam antenna array at 28 GHz.

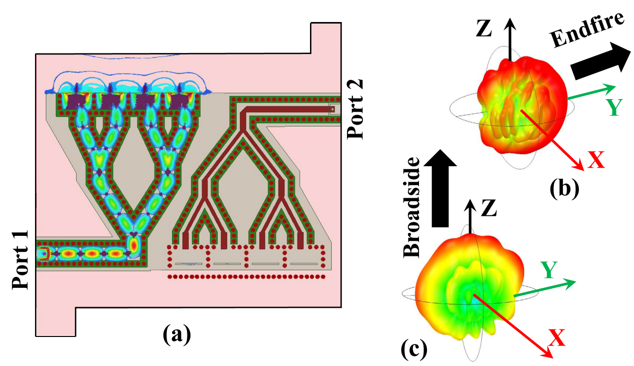


FIGURE 11. (a) Electric field distribution at 28 GHz with *port 1* excitation. 3D gain pattern with (b) port 1 and (c) port 2 excitation in the proposed dual beam antenna array.

III. RESULTS

The measured S-parameter of proposed full duplex antenna array along with the fabricated prototype is shown in Fig. 9. PNA-L series Network Analyzer (model no. N5234A) is used to measure the performance of the designed prototype. The proposed antenna resonates at 28 GHz with an in-band bandwidth of 500 MHz. The isolation obtained is better than 45 dB over the entire operating bandwidth. The measured results matches well with the simulated results. The fabricated prototype of the proposed full duplex antenna array is shown in top and bottom view in Fig. 9(b) and (c).

The simulated and measured normalized radiation pattern are plotted in Fig. 10 in both E- and H- plane at 28 GHz. A measured gain of the port 1 is 10.8 dBi and port 2 is 10.3 dBi. The sidelobe level for the antenna array is 13 dB

TABLE 3. Comparison of previous work with this work.

Parameter	Antenna	Size (λ_0)	Technique for isolation	Dielectric	Frequency	Gain	Isolation	Remarks
[3]	PIFA antenna	1.2 x 0.6 x 0.06	2 co-located antennas for Tx & Rx with large separation	–	2.5/ 3.5 GHz	4.8/ 3.9 dBi	20/ 35 dB	• Low gain, narrowband, large separation, larger footprint & 3D design. • Microwave frequency
[23]	HMSIW	–	Metallic via-wall	3.55	4.9/ 5.8 GHz	5.24/ 5.37 dBi	30 dB	• 2 different frequencies for Tx & Rx (Diplexing antenna). Not In-Band Full Duplex (IBFD). • Microwave frequency
[24]	Dual polarized slot	0.8 x 0.77 x 0.009	Differential feed	2.2	5.8 GHz	5.4/ 5.8 dBi	50 dB	• Additional Lumped capacitor gives 30 dB increase in isolation. • Microwave frequency
[25]	Half mode microstrip patch	0.75 x 1.57 x 0.03	Field Confinement & Defected Ground (DGN)	2.2	5.9 GHz	5.6 dBi	> 54 dB	• Array implementation is difficult. • Microwave frequency
[26]	8 x 8 patch array	–	2 co-located antenna for Tx & Rx with large separation	–	15 GHz	22.4 dBi	38 dB	• 16 Lumped resistor required for the design. • Microwave frequency
[27]	Microstrip fed slot	–	Duplexing slot & Low Noise Amplifier (LNA)	3.6	24 GHz	6 dBi	70 dB	• Additional LNA is used to increase isolation which makes array design difficult. • Millimeterwave frequency
[28]	Dual Polarized LWA slot	11.7 x 11.7 x 0.3	Orthogonal Polarization & Differential feed & coupler	3.0	28.5 GHz	20.5 dBi	51 dB	• Pillbox transition & coupler makes the feed network bulky. • Millimeter wave frequency.
[29]	Half mode microstrip	0.73 x 0.77 x 0.01	Defected Ground Structure	2.2	2.45 GHz	4 - 5 dBi	25 dB	• Low isolation. • Microwave frequency.
[30]	Microstrip patch	1.6 x 1.6	Beam forming network (BFN)	2.2	2.45 GHz	7 dBi	47 dB	• 3D structure, additional BFN. • Microwave frequency.
This Work	**HMSICL & HMSIW array**	**3.2 x 4.1 x 0.1**	**Physical separat--ion with wide coverage (end-fire & broadsie)**	**2.2**	**28 GHz**	**10.8 dBi**	**45 dB**	**• In-Band Full Duplex (IBFD) • No SMD element/ coupler or pillbox required. • Planar low-profile • Millimeter wave frequency.**

– Not mentioned in the literature.

below the main lobe. The cross-polarization level is below -30 dB for HMSICL cavity fed monopole antenna array with port 1 excitation and below -15 dB for HMSIW cavity antenna array with port 2 excitation. The efficiency of the HMSICL fed monopole antenna array is 88.7% and HMSIW excited slot antenna array is 92.2% respectively. The magnitude of electric field in the proposed IBFD antenna array is shown in Fig. 11(a) with *port 1* excitation, which depicts negligible interference in the full-duplex operation. The 3D gain pattern depicted in Fig. 11(b), (c) shows the radiated beam along the endfire direction in the transmit mode and radiated beam along the broadside direction in the receiving mode and vice-versa. Table 2 presents a comparison of the proposed work with reported works. Most of the antennas [3], [23], [24], [25], [26], [29], and [30] operate at lower microwave frequencies. Scaling these microstrip based antennas for high frequencies does not result in efficient antennas as microstrip designs result in spurious radiations and surface wave losses. Antenna designs [3], [23], [24], [25], [25], [27], [29], and [30] are low gain antennas. To be practically suitable for commercial and industrial applications at millimeter wave frequencies, antenna arrays with sufficiently high gain are required. In [23], two HMSIW antennas operates at two different frequencies. Hence, In-Band Full Duplex operation required for channel sharing and frequency re-use at millimeter wave frequency is not achieved in the design. The works in [24] and [26] require additional lumped SMD capacitors and resistors, [27] incorporates Low Noise Amplifier (LNA) and [30] uses additional beamforming network to achieve isolation. Antenna design in [3], pillbox transition in [28] and cables in [30] make design bulky and occupy larger footprint. In view of the above stated works, the presented work is a simple, planar and compact design that does not utilize couplers, Low Noise Amplifier (LNA), lumped capacitors or resistors to achieve isolation. Moreover, the designed array achieves In-Band Full Duplex (IBFD) performance in a single frequency band enabling channel sharing and efficient spectrum re-use by making time division duplex (TDD) realizable for both simultaneously transmit and receive (STAR). The antenna elements in the array is found to be susceptible to frequency shift due to the aberrations in via-hole fabrication. Due to the inclusion of blind feeding via for feed, vertical misalignment between the prepeg may lead to losing conductivity. Hence, fabrication of the designed prototype must be carried out with utmost care.

IV. CONCLUSION

This paper presents an In-Band Full Duplex (IBFD) antenna array that utilizes simplest passive signal interference cancellation technique (SIC) for duplexing operation. The novelty of the work lies in designing a half mode antenna in Substrate Integrated Coaxial Line (SICL) technology and its integration with HMSIW antenna to deliver in-band full-duplex operation. The proposed HMSICL cavity based antenna is simplest known endfire antenna designed using SICL technology. The antennas designed in two technologies are arranged in a close proximity to ensure smaller footprint at Ka-band. High isolation is obtained in the proposed design by utilizing the orientation of the antennas to minimize the interference of the radiated beam in space. This work serves as a proof-of-concept to design larger array with high gain suitable for relays at Ka-band frequencies.

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