IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 30, 2020, accepted April 21, 2020, date of publication April 24, 2020, date of current version May 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2990205

Wideband Asymmetric Coplanar Strip Fed Antennas With Pattern Diversity for mmWave 5G Base Stations

M. IDREES MAGRAY[1], (Graduate Student Member, IEEE),
G. S. KARTHIKEYA[2], (Graduate Student Member, IEEE),
KHALID MUZAFFAR[1], (Member, IEEE), SHIBAN KISHEN KOUL[2], (Life Fellow, IEEE),
AND AYAZ HASSAN MOON[1], (Member, IEEE)
[1]Department of Electronics and Communication Engineering, Islamic University of Science and Technology (IUST), Awantipora 192122, India
[2]Centre for Applied Research in electronics, IIT Delhi, New Delhi 110016, India

Corresponding author: G. S. Karthikeya (karthikeyaglr@gmail.com)

ABSTRACT A compact asymmetric coplanar strip (ACS)-fed mmWave 5G antenna with 6.5-7.5 dBi end-fire gain is presented in this paper. The proposed antenna is wideband, operating from 26-32 GHz with fractional bandwidth of 20.7%. The proposed single element antenna has dimensions of 6×10 mm^2 demonstrating small physical and electrical footprint. The antenna achieves 1-dB gain bandwidth of 20.7% which demonstrates pattern integrity over whole operating band. The reported antenna also achieves reasonable gain for the available aperture. In order to achieve pattern diversity, a shared ground compact two-port antenna topology is next presented for beam switching at ±30°. In addition to this, a quasi-stacked beam switching module integrated with low cost 3D-printed scaffolding with wide angular coverage is proposed with adequate technical justification.

INDEX TERMS Compact, ACS-fed antenna, mmWave 5G, end-fire, base station, pattern diversity.

I. INTRODUCTION

Fifth generation cellular networks (5G) promise high data rates, almost 1000 times as compared to fourth generation mobile networks (4G) [1]. New frequency bands are being allocated to 5G communication, especially 28 GHz frequency band which is considered to be one of the hot candidates for 5G cellular communication especially in the USA, Europe and Korea [2].

The main challenge with utilization of higher frequencies is high free space path loss and penetration losses as reported in [3]. In order to mitigate this problem, antenna architectures should possess high gain on both the access point and cellular device. In addition to this, a compact module is necessary for typical base station or access point to conform to industry standards of commercial ceiling mounted access points. It is also recommended to achieve wide impedance bandwidth to support multiple standards across the 5G spectrum to be future proof.

Several antenna designs have been reported on mmWave 5G frequencies in [4]–[7] but they have large physical footprint leading to a higher occupied volume which might not be suitable for compact base stations or access points per se. Also, gain of these antenna modules is relatively low for the available aperture. Unlike coplanar waveguide (CPW)-fed mmWave 5G antennas, for instance [8], [9], asymmetric coplanar strip (ACS)-fed antennas occupy only half of the physical footprint without significant loss in gain, hence achieving the compactness. To the best of our knowledge, ACS-feeding technique has been implemented at lower frequencies only like in [10], [11]. This paper, therefore presents a proof-of-concept design at mmWave frequencies with compact antenna architecture and higher impedance bandwidth.

In this paper, a compact ACS-fed antenna for 5G base stations is proposed. The proposed antenna operates over a wideband covering mmWave frequencies from 26-32 GHz. Forward end-fire gain of 6.5-7.5 dBi is achieved for the available aperture. The proposed antenna exhibits high pattern integrity and stable radiation patterns with front-to-back

The associate editor coordinating the review of this manuscript and approving it for publication was Dušan Grujić.

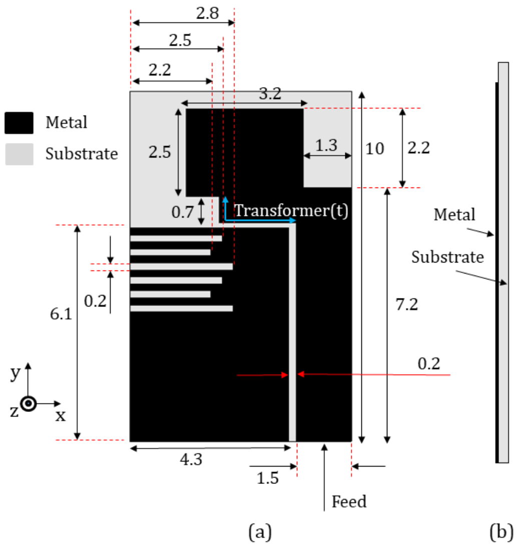


FIGURE 1. Schematics of the proposed ACS-fed mmWave 5G antenna (a) Top view and (b) Side view (All dimensions are in mm).

ratio of more than 13 dB across the operating spectrum. Moreover, a quasi-stacked architecture using the aforementioned element and shared ground antennas is presented in the following sections.

II. COMPACT ACS-FED ANTENNA

The proposed ACS-fed antenna is illustrated in Fig.1 which is designed on 10 mil (0.254 mm) thick Rogers 5870 substrate with dielectric constant (ε_r) of 2.33 ± 0.02 and dielectric loss tangent of 0.0012. In order to minimize cross polarization radiation level in the end-fire, electrically thin substrate of 0.025 λ thickness was chosen. Substrate of low relative permittivity was chosen in order to keep surface wave modes to minimum [12]. The proposed antenna is fed by a 50Ω characteristic impedance ACS-feedline, designed according to standard calculations, whose width is chosen to be 1.5 mm with gap width of 0.2 mm which is feasible with industry standard chemical etching process [10, 11]. The 50Ω feed is connected to an impedance transformer of 65.4Ω feeding the rectangular shaped radiator of 85.5Ω for better impedance matching. The proposed ACS-fed antenna has a small physical footprint with dimensions of $0.6\lambda \times 1\lambda$ at 28GHz including the feedline.

Full-wave antenna simulations were carried out using CST Microwave Studio® Software. Topology of the antenna consists of an unbalanced ACS-line, feeding the rectangular shaped radiator whose dimensions are around quarter wavelength at 28 GHz which inherently produces an undesired beam tilt effect. In order to compensate this beam tilt produced by unbalanced feed, offset of 1.3 mm is introduced in the radiator which produces unidirectional beam in end-fire. Separation of 0.8 λ is chosen between feeding plane and the radiator to avoid grounding with the clamps of the end-launch connector. Photograph of the proposed fabricated antenna is depicted in Fig.2. Substrate was extended from both the sides of the fabricated prototype in order to accommodate the industry standard 2.92 mm bulky end-launch connector which operates up to 40 GHz.

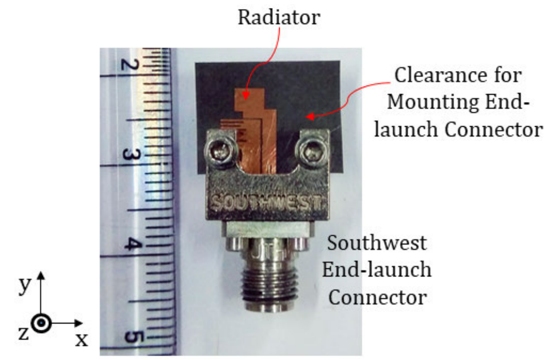


FIGURE 2. Photograph of the proposed ACS-fed antenna.

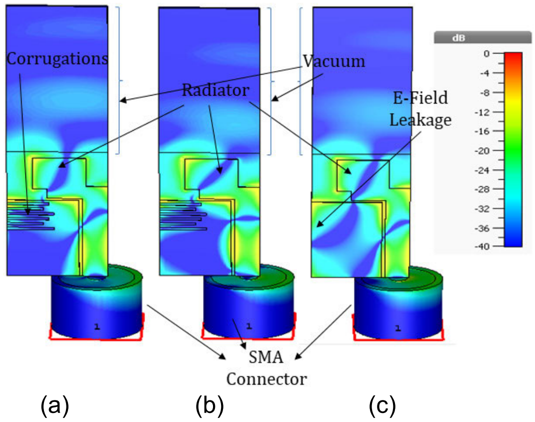
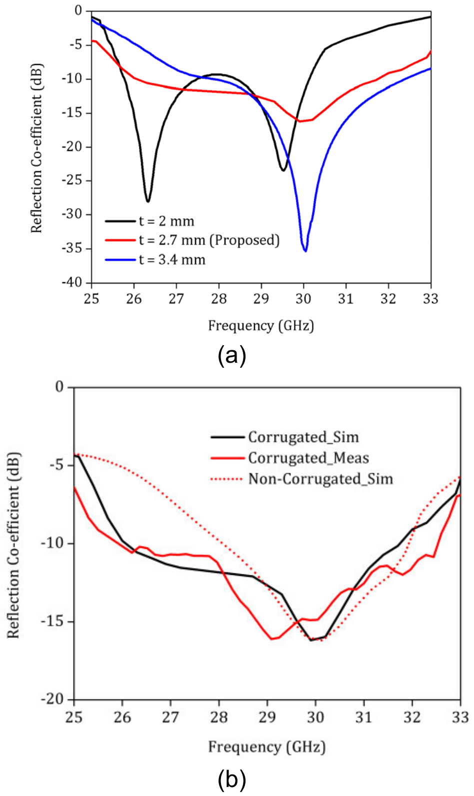


FIGURE 3. E-field plots at (a) 26 GHz, (b) 32 GHz and (c) 28 GHz.

Varying length corrugations were inserted in the ground plane in order to concentrate the E-field towards the radiating aperture thereby reducing side-lobes. E-field plots at various frequencies for ACS-fed mmWave 5G antenna with and without corrugations are illustrated in Fig.3. The plots illustrate the quasi-traveling wave behavior of antenna which contains the E-plane (XY-plane) parallel to the substrate. It can be also noticed that the radiator is uniformly irradiated irrespective of the frequency of operation, therefore providing wider impedance bandwidth. Bulky end-launch connector was modeled in simulations with SMA connector thereby producing less disparity between simulated and measured results.

Variation of the length of impedance transformer (t) on the input reflection co-efficient is illustrated in Fig. 4(a). The optimal length of impedance transformer for higher impedance bandwidth was determined to be 2.7 mm. Measured results of the proposed antenna were carried out using Agilent PNA E8364C. Simulated and measured input reflection co-efficients of the proposed ACS-fed mmWave 5G antenna is depicted in Fig.4 (b). Measured impedance



(a)

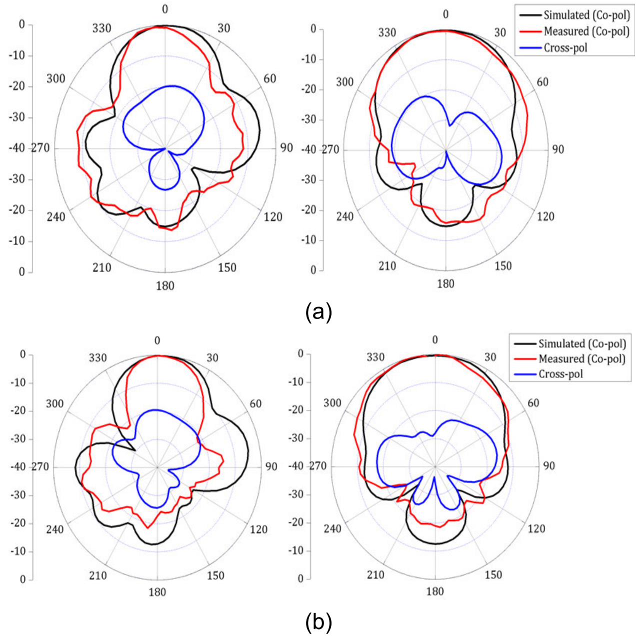
(b)

FIGURE 4. **(a) Input reflection co-efficient variation with parameter,'t' and (b) Input reflection co-efficient of the proposed antenna.**

bandwidth of the proposed antenna is from 26-32 GHz with fractional bandwidth of 20.7%. Also, proposed antenna with corrugated ground achieves higher impedance bandwidth than its non-corrugated counterpart. Discrepancies between simulated and measured results may be due to fabrication tolerances, inhomogeneity of dielectric constant of the substrate in Ka-band and the characteristic impedance deviation from 50Ω of the end-launch connector used for measurements [8], [13].

Measured results were carried out in an anechoic chamber using Keysight standard horn R281B as transmitter. Simulated and measured radiation patterns of the proposed antenna in both the principal planes, i-e-, E-plane (XY-plane) and H-plane (YZ-plane) are shown in Fig.5 at 28 and 30 GHz.

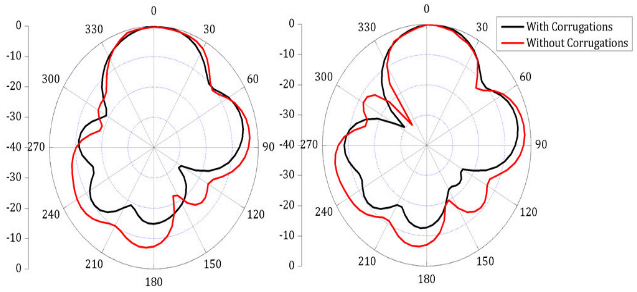
Radiation patterns with high pattern integrity are achieved in both the planes as evident from Fig.5. Disparity between simulated and measured data might be due to polarization alignment errors and scattering due to electrically large adapters employed for pattern measurements. Since the ground plane is electrically close (0.02 λ) to radiator, radiation patterns are uni-directional in nature. Also, the width of ground plane is large enough to make the antenna radiate in end-fire direction. Front-to-back ratio is more than 13 dB for the whole operating mmWave band. Cross-polarization in both the principal planes is less than −18 dB indicating strong linearly polarized antenna. Due to unbalanced ground in ACS-feeding, a small side-lobe of value less than



(a)

(b)

FIGURE 5. **Simulated and measured co-pol and cross-pol radiation patterns in XY and YZ plane at (a) 28 GHz and (b) 30 GHz.**



(a)

(b)

FIGURE 6. **Radiation patterns of proposed antenna with and without corrugations at (a) 28 GHz and (b) 30 GHz.**

1.5 dB can be noticed in the E-plane as compared with the main lobe of proposed antenna in end-fire direction. The measured half-power beamwidth is around 50° ± 5° in the E-plane (XY-plane) and 70° ± 5° in the H-plane (YZ-plane). Moreover, Fig.6 illustrates the reduction of side lobes by insertion of varying length corrugations.

The proposed antenna possesses end-fire gain of 6.5-7.5 dBi indicating high gain for the available aperture as compared to reported end-fire antennas [14], [15]. 3D-radiation plots of the proposed antenna are illustrated in Fig.7 at frequencies 28 and 30 GHz thus providing additional insight about the radiation characteristics of proposed ACS-fed mmWave 5G antenna. Moreover, gain and radiation efficiency of the proposed antenna is depicted in Fig.8. Gain varies between 6.5-7.5 dBi over the whole operating band. Since, corrugated ground plane is electrically large enough to create forward radiation, therefore high gain is observed. Also, radiation efficiency is greater than 88% over the entire

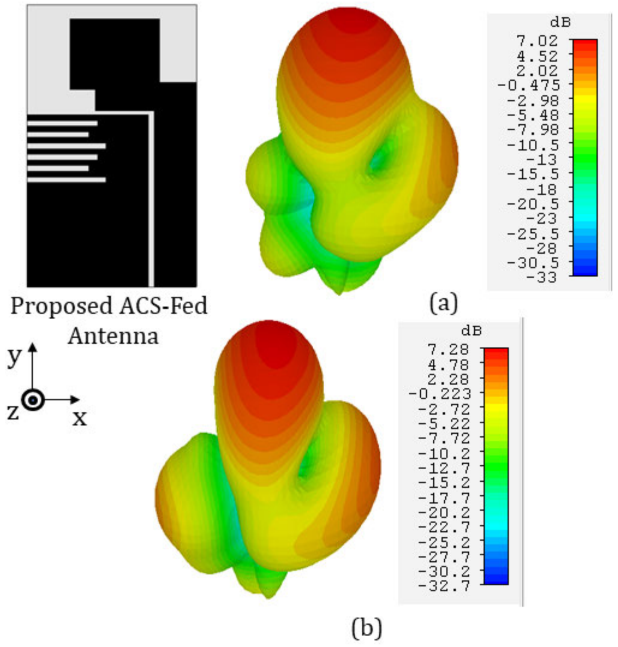


FIGURE 7. 3D-radiation plots at (a) 28 GHz and (b) 30 GHz.

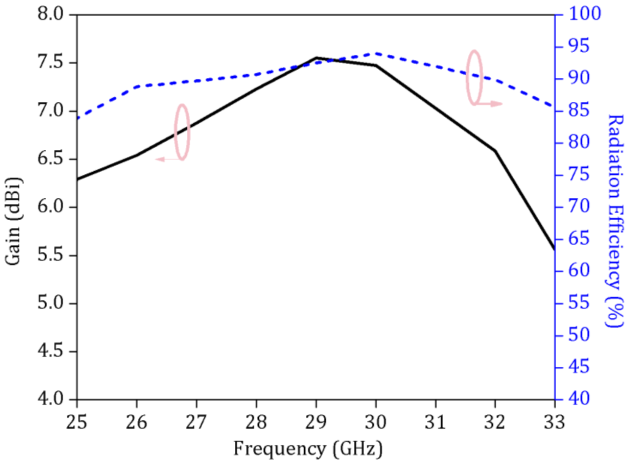


FIGURE 8. Forward gain and radiation efficiency of the proposed ACS-fed mmWave 5G antenna.

operating band. The loss in radiation efficiency is mainly due to dielectric loss tangent of the substrate as the antenna possesses end-fire radiation pattern. The 1-dB gain bandwidth of the proposed antenna is 20% indicating high pattern integrity over the entire operating band.

The proposed antenna occupies small physical footprint with high end-fire gain and pattern integrity compared with other reported planar designs, as illustrated in Table 1.

III. SHARED GROUND TWO-PORT ANTENNA MODULE

The primary objective of designing the two port shared ground antenna module is to attain the beam switching at ±30° in E-plane, which is conventionally achieved by physically orienting antenna elements with separate grounds.

TABLE 1. Comparison of the proposed antenna design with other reported designs.

REF	SOA	Gain (dBi)	1-dB GB (%)	Feeding Type	FTBR
[5]	12 × 12	3-4.5	NA	CPW	NA
[6]	NA	8-10	NA	CPS	NA
[7]	NA	9-11.3	10.5	Microstrip	18
[8]	11 × 20	6-7	20	CPW	> 12
[9]	10.5 × 10	6-7	20	CPW	> 12
[16]	20 × 19.2	9	9.8	Microstrip	13
[17]	NA	4-6.5	6.3	Microstrip	19
[18]	16 × 14	2.7-5	28.6	CPW	< 10
PW	**6 × 10**	**6.5-7.5**	**20.7**	**ACS**	**> 13**

* SOA = Size of antenna (in mm^2), GB = Gain bandwidth, FTBR = Front-to-back ratio (in dB), NA = Not available, CPS = Coplanar stripline, PW = Proposed work.

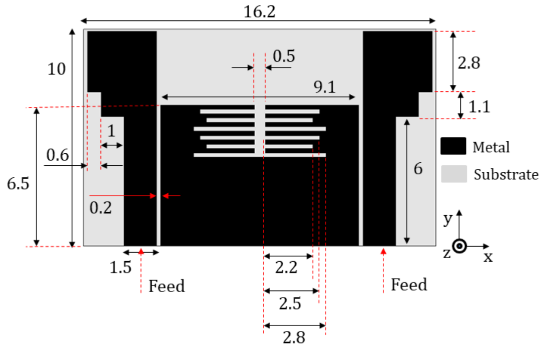


FIGURE 9. Schematics of the proposed ACS-fed mmWave 5G two port antenna module (All dimensions are in mm).

In order to miniaturize this beam switching module, shared ground module is investigated. Two-port antenna module is designed on 10 mil thick Rogers 5870 substrate. The proposed topology consists of two identical ACS-fed compact antennas sharing the common ground in mirrored configuration. The dimensions of the proposed two port antenna design are 1.0λ × 1.6λ at 28GHz. The antenna topology is symmetrical about the Y-axis. Schematics of the proposed ground shared two port antenna is depicted in Fig.9.

Each antenna element consists of stepped radiator which is fed by 50 Ω ACS feedline. The stepped configuration helps in achieving wide impedance bandwidth in the shared ground context [10]. Here, the unbalanced feedline aids in obtaining beam tilt which mainly depends on length of the ground plane and offset of radiator with respect to phase center of the module. The size of stepped radiator and shared ground is optimized to attain 30° beam tilt as a proof of concept. Since, asymmetrical shared ground plane is electrically close to either of the two port antennas, thereby reflecting the forward beam, hence producing desired beam tilt. Varying length corrugations were introduced in the ground which

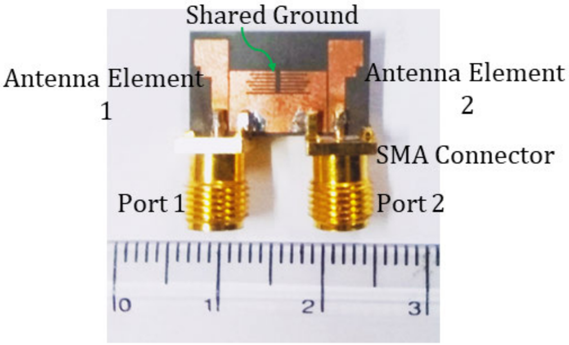
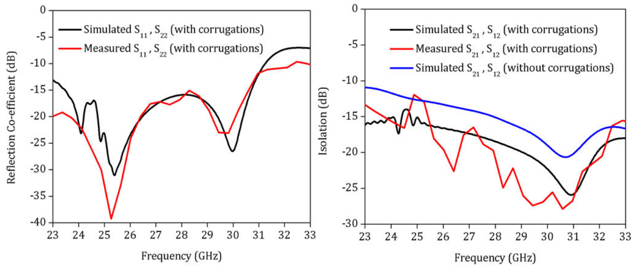


FIGURE 10. Photograph of the fabricated two port ground shared antenna.

helps in reduction of mutual coupling between two closely spaced antenna elements (0.9λ) across the entire operating frequency band. Proposed antenna geometry is fabricated and photograph is shown in Fig.10.

Since the space for mounting end launch connectors at both the antenna ports is limited, standard 50Ω SMA ports are used for measurement purposes which are operational in the Ka-band. The insertion loss is typically close to 0.5 to 1 dB when the typical SMA connector is extended up to 30 GHz. Thin-tip soldering rod was used to create the coax to ACS transition, hence avoiding the lead inductance offered in conventional low frequency designs. Simulated and measured input reflection co-efficients of the proposed antenna architecture are illustrated in Fig. 11. Both the antenna elements operate from 23 to 32 GHz with fractional bandwidth of 32.7%. Mutual coupling between the antenna elements is less than 13 dB in the entire operating band. Varying length corrugations provides the additional path for the flow of surface currents from one antenna to another thereby enhancing isolation by almost 4 dB over the whole operating frequencies. Fig. 11 (a) and (b) depicts the simulated and measured input reflection co-efficient and isolation respectively.



(a) (b)

FIGURE 11. (a) Input reflection co-efficient and (b) Isolation plot for both antenna elements.

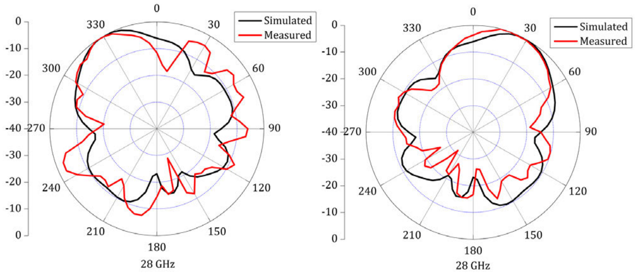


FIGURE 12. Simulated and measured radiation patterns in XY plane when each antenna port is excited at 28 GHz.

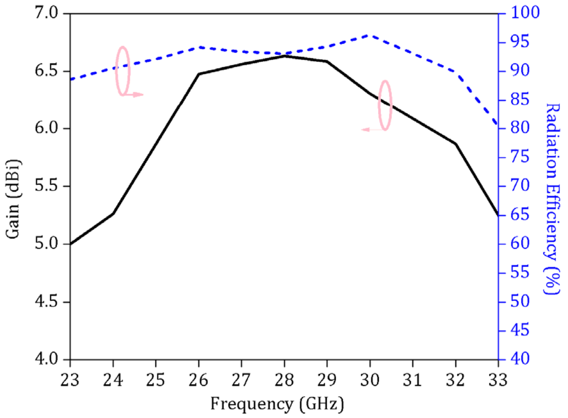


FIGURE 13. End-fire gain and radiation efficiency of either of the two port ground shared antenna.

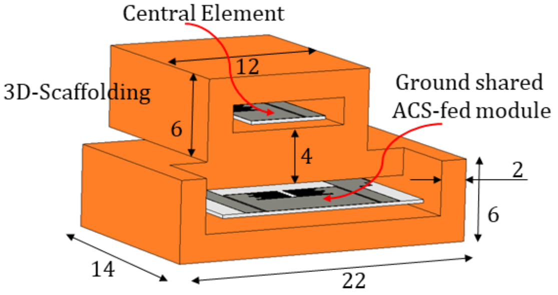


FIGURE 14. Schematics of the proposed ACS-fed mmWave 5G pattern diversity module (All dimensions are in mm).

Radiation patterns with high pattern integrity for both the antenna elements in XY-plane (E-plane) are shown in Fig.12 at 28 GHz. Measured beamwidth for each of the antenna elements is 40° ± 5° in the main lobe. Proper beam orientation at ±30° can be noticed which is mainly due to reflection caused by asymmetric ground plane. Front-to-back ratio of more than 18 dB is achieved for both the antenna elements, hence proving its suitability for base stations or access point applications.

End-fire gain of the proposed two port antenna geometry for the main lobe ranges between 5 – 6.8 dBi over the entire operating band as depicted in Fig. 13. Due to leakage of radiations occurring between two antenna elements through shared ground plane, gain of either of the antenna element is deteriorated in comparison with single element topology discussed in the previous section. The 1-dB gain bandwidth is around 24.5% in the operating band, indicating high pattern integrity.

IV. PATTERN DIVERSITY MODULE

A three dimensional compact antenna topology is proposed for mmWave 5G base stations. Schematics of the proposed antenna architecture is illustrated in Fig. 14 with

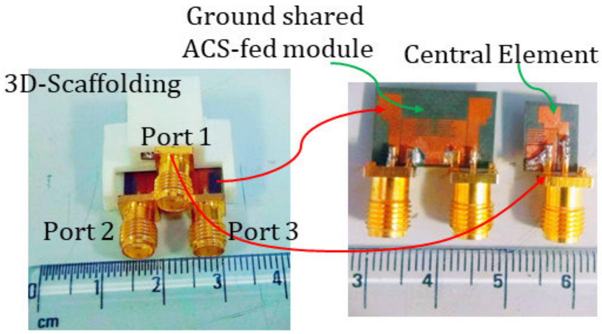
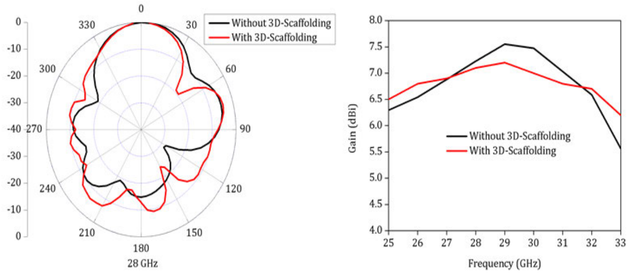
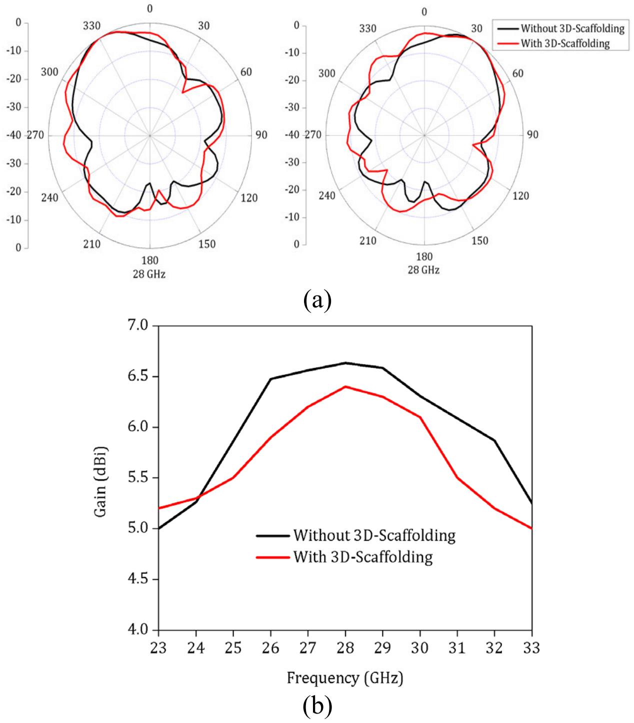


FIGURE 15. Photograph of the fabricated prototype.



(a) (b)

FIGURE 16. (a) Radiation pattern and (b) Gain plot of the central element ACS-fed antenna.



(b)

FIGURE 17. (a) Radiation patterns and (b) Gain plot of the two port ground shared antennas.

corresponding photograph of the fabricated prototype in Fig. 15. The central element is placed above the shared ground module and the separation is around 0.4 λ which is optimized for attaining better isolation.

Compact antenna architecture is placed in a fabricated three dimensional housing made of Poly Lactic Acid (PLA). PLA has a dielectric constant of around 2.56 with a dielectric loss tangent of 0.018 at 28 GHz [19]. The transmission loss of the 3D-printed scaffolding is negligible as demonstrated in the Figures 16 and 17 below with and without scaffolding, since the transmission loss is only 0.5-0.75 dB across the band of interest. It is also interesting to note that the gain deterioration due to the integration of scaffolding is only 0.5 dB, which is justified in a practical deployment scenario. The gain deterioration is minimal irrespective of the port which is being excited. The measurements were all performed with the integrated scaffolding hence proving the aforementioned comments to be true.

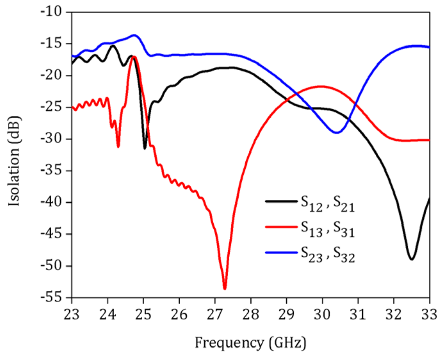


FIGURE 18. Mutual coupling between antenna elements placed in mmWave 5G pattern diversity module.

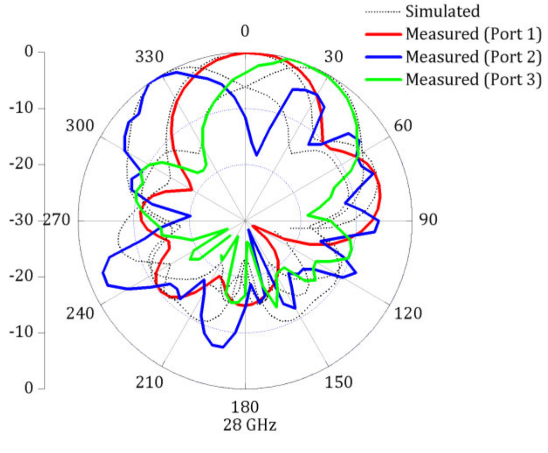


FIGURE 19. Radiation patterns at 28 GHz.

For central element in pattern diversity module, physical offset of 6 mm is introduced in the end-fire direction from the feed plane of shared ground antenna architecture in order to reduce the quasi-waveguide effect caused by the ground shared module [16]. Mutual coupling between the antenna elements is less than 14 dB across the entire operating band as illustrated in Fig.18. Radiation pattern of the pattern diversity module at 28 GHz is depicted in Fig. 19. Uniform coverage of −45° to +45° is attained over the entire operating band. Shared ground module directs beam at ±30° and the central

TABLE 2. Comparison of the proposed pattern diversity architecture with other reported designs.

REF	Frequency (GHz)	Fractional Bandwidth (%)	Angular Coverage
[7]	28	18.1	±30°
[20]	60	11.5	±35°
[21]	60	11.5	±26°
[22]	60	11.5	±30°
[23]	28	36.2	±45°
[24]	28	10	±45°
PW	**28**	**20.7**	**±45°**

element shoots the beam at 0° thus obtaining the uniform coverage of 90°. Furthermore, Table 2 illustrates the comparison between proposed pattern diversity architecture and various reported designs for mmWave 5G base stations.

V. CONCLUSION

A compact three dimensional ACS-fed antenna topology is proposed for mmWave 5G base stations. Proposed antenna architecture consists of central element which is placed above the ground shared module for beam steering at 0°, $+30°$ and $-30°$. Central antenna element is wideband with fractional bandwidth of 20.7%. Also, the antenna acquires high peak gain of 7.5 dBi for the available physical size. Ground shared module consists of two port ACS-fed antennas with fractional bandwidth of 32.7%. Thus, the proposed antenna configuration is a suitable candidate for mmWave 5G base stations.

REFERENCES

[1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[2] J. Kurvinen, H. Kahkonen, A. Lehtovuori, J. Ala-Laurinaho, and V. Viikari, "Co-designed mm-wave and LTE handset antennas," *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1545–1553, Mar. 2019.

[3] W. Hong, K.-H. Baek, Y. Lee, Y. Kim, and S.-T. Ko, "Study and prototyping of practically large-scale mmWave antenna systems for 5G cellular devices," *IEEE Commun. Mag.*, vol. 52, no. 9, pp. 63–69, Sep. 2014.

[4] Z. Wani, M. P. Abegaonkar, and S. K. Koul, "A 28-GHz antenna for 5G MIMO applications," *Prog. Electromagn. Res. Lett.*, vol. 78, pp. 73–79, 2018.

[5] S. F. Jilani, S. M. Abbas, K. P. Esselle, and A. Alomainy, "Millimeter-wave frequency reconfigurable T-shaped antenna for 5G networks," in *Proc. IEEE 11th Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2015, pp. 100–102.

[6] R. A. Alhalabi and G. M. Rebeiz, "Differentially-fed millimeter-wave yagi-uda antennas with folded dipole feed," *IEEE Trans. Antennas Propag.*, vol. 58, no. 3, pp. 966–969, Mar. 2010.

[7] Z. Wani, M. P. Abegaonkar, and S. K. Koul, "Millimeter-wave antenna with wide-scan angle radiation characteristics for MIMO applications," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 29, no. 5, May 2019, Art. no. e21564.

[8] G. S. Karthikeya, M. P. Abegaonkar, and S. K. Koul, "CPW fed wideband corner bent antenna for 5G mobile terminals," *IEEE Access*, vol. 7, pp. 10967–10975, 2019.

[9] G. S. Karthikeya, M. P. Abegaonkar, and S. K. Koul, "A wideband conformal antenna with high pattern integrity for mmWave 5G smartphones," *Prog. Electromagn. Res. Lett.*, vol. 84, pp. 1–6, 2019.

[10] X. Li, X.-W. Shi, W. Hu, P. Fei, and J.-F. Yu, "Compact triband ACS-fed monopole antenna employing open-ended slots for wireless communication," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 388–391, 2013.

[11] R. Rajkumar and K. Usha Kiran, "A compact ACS-Fed mirrored L-shaped monopole antenna with SRR loaded for multiband operation," *Prog. Electromagn. Res. C*, vol. 64, pp. 159–167, 2016.

[12] G. P. Gauthier, A. Courtay, and G. M. Rebeiz, "Microstrip antennas on synthesized low dielectric-constant substrates," *IEEE Trans. Antennas Propag.*, vol. 45, no. 8, pp. 1310–1314, Aug. 1997.

[13] C. Zhang, J. Gong, Y. Li, and Y. Wang, "Zeroth-Order-Mode circular microstrip antenna with patch-like radiation pattern," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 3, pp. 446–449, Mar. 2018.

[14] J. Puskely, J. Lacik, Z. Raida, and H. Arthaber, "High-gain dielectric-loaded vivaldi antenna for K_a -Band applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 2004–2007, 2016.

[15] K. Yang, A. Loutridis, X. Bao, P. McEvoy, and M. J. Ammann, "A coplanar vivaldi antenna with integrated filter for ka-band," in *Proc. Loughborough Antennas Propag. Conf. (LAPC)*, Nov. 2016, pp. 1–4.

[16] G. S. Karthikeya, M. P. Abegaonkar, and S. K. Koul, "Pattern diversity of path loss compensated antennas for 5G base stations," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 29, no. 8, Aug. 2019, Art. no. e21800.

[17] R. A. Alhalabi and G. M. Rebeiz, "High-ef?ciencyangled-dipoleantennas for millimeter-wave phased array applications," *IEEE Trans. Antennas Propag.*, vol. 56, no. 10, pp. 3136–3142, Oct. 2008.

[18] S. F. Jilani, B. Greinke, Y. Hao, and A. Alomainy, "Flexible millimetre-wave frequency reconfigurable antenna for wearable applications in 5G networks," in *Proc. URSI Int. Symp. Electromagn. Theory (EMTS)*, Aug. 2016, pp. 846–848.

[19] G. Boussatour, P.-Y. Cresson, B. Genestie, N. Joly, and T. Lasri, "Dielectric characterization of polylactic acid substrate in the frequency band 0.5–67 GHz," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 5, pp. 374–376, May 2018.

[20] A. Dadgarpour, B. Zarghooni, B. S. Virdee, and T. A. Denidni, "One- and two-dimensional beam-switching antenna for millimeter-wave MIMO applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 564–573, Feb. 2016.

[21] A. Dadgarpour, B. Zarghooni, B. S. Virdee, and T. A. Denidni, "Beam-deflection using gradient refractive-index media for 60-GHz end-fire antenna," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3768–3774, Aug. 2015.

[22] Z. Briqech, A.-R. Sebak, and T. A. Denidni, "Wide-scan MSC-AFTSA array-fed grooved spherical lens antenna for millimeter-wave MIMO applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2971–2980, Jul. 2016.

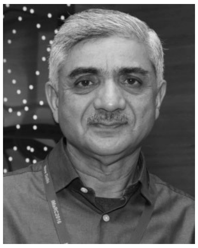
[23] S. X. Ta, H. Choo, and I. Park, "Broadband printed-dipole antenna and its arrays for 5G applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2183–2186, 2017.

[24] K. Gulur Sadananda, M. P. Abegaonkar, and S. K. Koul, "Gain equalized shared-aperture antenna using dual-polarized ZIM for mmWave 5G base stations," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 6, pp. 1100–1104, Jun. 2019.

M. IDREES MAGRAY (Graduate Student Member, IEEE) received the B.Tech. degree in electronics and communication engineering from the Islamic University of Science and Technology (IUST), Awantipora, in 2018. He is currently pursuing the master's degree with National Chiao Tung University (NCTU), Taiwan. He received INAE fellowship for two months and during that tenure he worked under the supervision of Prof. S. K. Koul. He worked on various projects at CARE, IIT Delhi, under the guidance of Prof. S. K. Koul. He has authored or coauthored several articles in peer-reviewed journals and conference proceedings. His research interests include co-designed 4G/5G antennas for smartphones, mmWave antennas for mobile terminals and base stations, and antenna in packaging (AiP). He received the Best Project Competition Award in InCAP 2019.

G. S. KARTHIKEYA (Graduate Student Member, IEEE) received the bachelor's degree in electronics and communication engineering from Visvesvaraya Technological University, Belgaum, in 2010, and the master's degree (Hons.) in microwave engineering from the University of Kerala, in 2012. He worked as an Assistant Professor with Visvesvaraya Technological University, from 2013 to 2016, where he established the Antenna Architects' lab. He joined the Centre for Applied Research in Electronics as a Ph.D. Student in January 2017 and defended his thesis in December 2019. He is currently a Postdoctoral Fellow with IIT Delhi. He has authored or coauthored more than 45 articles in peer-reviewed journals and conference proceedings. He has also filed three Indian patents and a U.S. patent. He serves as the Reviewer of ACES, IEEE ACCESS and Cambridge's IJMWT. He has served as an event secretary in the IEEE MTT-S student chapter at IIT Delhi, from 2017 to 2019.

KHALID MUZAFFAR (Member, IEEE) received the B.Tech. degree in electronics and communication and the M.Tech. degree in communication and IT from NIT, Srinagar, India, in 2004 and 2006, respectively, and the Ph.D. degree from the Centre for Applied Research in Electronics, IIT Delhi, India, in June 2017. He was a Field and Maintenance Engineer with Ericsson India Pvt. Ltd., from July 2006 to July 2007. He joined IUST, Awantipora, as an Assistant Professor, in August 2007. He is currently working as an AICTE coordinator and a NBA coordinator with IUST, Awantipora. His research interests are microwave antenna design, and applications of thermal imaging for microwave field imaging.



SHIBAN KISHEN KOUL (Life Fellow, IEEE) received the B.E. degree in electrical engineering from the Regional Engineering College, Srinagar, in 1977, and the M.Tech. and Ph.D. degrees in microwave engineering from the Indian Institute of Technology Delhi, New Delhi, India, in 1979 and 1983, respectively.

He has served as a Dr. R. P. Shenoy Astra Microwave Chair Professor at the Centre for Applied Research in Electronics. He also served as the Deputy Director (strategy & planning) at IIT Delhi, from 2012 to 2016, and the Deputy Director (Strategy & Planning, International affairs and R&D) at the Indian Institute of Technology Jammu, from 2017 to 2020. He has served as the Chairman of M/S Astra Microwave Pvt. Ltd., a major private company involved in the Development of RF and Microwave systems in India, from 2009 to 2019. He is currently an Emeritus Professor with the Centre for Applied Research in Electronics, IIT Delhi, where he is involved in teaching and research activities. He has delivered more than 270 invited technical talks at various international symposia and workshops. He has successfully completed 34 major sponsored projects, 52 consultancy projects, and 58 Technology Development Projects. He is author/coauthor of 446 research articles, ten state-of-the art books, and three book chapters. He holds ten patents and six copyrights. His research interests include RF MEMS, high frequency wireless communication, microwave engineering, microwave passive and active circuits, device modeling, and millimeter wave IC design and reconfigurable microwave circuits including antennas.

Dr. Koul is a Fellow of the Indian National Academy of Engineering (INAE) and a Fellow of the Institution of Electronics and Telecommunication Engineers (IETE). He is a member of India Initiative team of IEEE MTT-S, Membership Services Regional Co-coordinator Region-10, the Vice Chair Sight Adhoc Committee, Member awards committee, and Nomination and Appointments committee. He has served as a Distinguished Microwave Lecturer of IEEE MTT-S for the period 2012–2014 and a Distinguished Microwave Lecturer-Emeritus of IEEE MTT-S, in 2015. He was a recipient of Gold Medal by the Institution of Electrical and Electronics Engineers Calcutta, in 1977; the S. K. Mitra Research Award from the IETE for the best research paper, in 1986; the Indian National Science Academy (INSA) Young Scientist Award, in 1986; the International Union of Radio Science (URSI) Young Scientist Award, in 1987; the top Invention Award of the National Research Development Council for his contributions to the indigenous development of ferrite phase shifter technology, in 1991; the VASVIK Award for the development of Ka- band components and phase shifters, in 1994; Ram Lal Wadhwa Gold Medal from the Institution of Electronics and Communication Engineers (IETE), in 1995; the Academic Excellence Award from Indian Government for his pioneering contributions to phase control modules for Rajendra Radar, in 1998, the Shri Om Prakash Bhasin Award in the field of Electronics and Information Technology, in 2009, the Teaching Excellence Award from IIT Delhi, in 2012, the Award for contributions made to the growth of smart material technology by the ISSS, Bangalore, in 2012, the Vasvik Award for the contributions made to the area of Information, Communication Technology (ICT), in 2012, the M. N. Saha Memorial Award from the IETE for the best application oriented research paper, in 2013; and the IEEE MTT Society Distinguished Educator Award in 2014. He is the Chief Editor of the *IETE Journal of Research* and an Associate Editor of the *International Journal of Microwave and Wireless Technologies* (Cambridge University Press).

AYAZ HASSAN MOON (Member, IEEE) received the bachelor's degree from the Engineering College, Srinagar, in 1980, the Post-Graduate Diploma and M.Tech. degrees in electronics design and technology from IISC Bangalore, in 1982 and 1993, respectively, and the Ph.D. degree from the Department of Electronics and Instrumentation, Kashmir University, in 2016.

He is currently serving as a Professor with the Department of Electronics and Communication Engineering, the Dean of the School of Engineering and Technology, the Project Coordinator TEQIP-III, and the Director IT and Support Services at IUST, Awantipora. He superannuated as a Scientist-G and Executive Directorate NIELIT Srinagar/Jammu, an Institution under Ministry of Electronics and Information Technology, (MeitY) Government of India, after rendering around 30 years of service in the same organization. Overall, he has experience of over 35 years in various fields, including six years in the Electronics industry and rest Administering Technical Organization, IT-HRD, Academics, Capacity Building, Consultancy, Advisory and R&D. He has participated and presented articles both at the international and national conferences on many occasions. Represented India on two occasions to present India Country report on Mutual Recognition of IT qualification among APEC countries in SIVAT, Seoul, South Korea, organized by HRD Korea, in 2006, and in Tokyo, Japan, organized by IPA Japan, in 2011. He has involved in the execution of various projects to the extent of Rs. 1000 crores in the last ten years of NIELIT. As an IT Advisor, he has been actively involved in the appraisal/technical evaluation of e-Governance projects of Jd&K state, including SWAN, SDC and CCTNS, traffic lights in Srinagar and Jammu cities, and so on. He has been a Chief Investigator of IECT projects, most recent being Smart Class Room Project of J&K Education Department, capacity building in ESDM, setting-up of computer forensics lab, NPR project, R&D projects on wireless sensor networks, rural trainings for employability in J&K state, repair and maintenance of hospital's equipments, and so on. He has served on academic boards of various universities, apart from being a member of J&K state e-Governance agency, a member task-force on e-Governance implementation in Sheri-Kashmir Agriculture University, Member IEEE, Fellow IEEE, and NAAC Assessor.

• • •