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

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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 \times 10 \text{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 \pm 30^\circ. 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.

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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
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 ($\varepsilon_r$) 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 $\lambda$ 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 50 $\Omega$ 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 50 $\Omega$ feed is connected to an impedance transformer of 65.4 $\Omega$ feeding the rectangular shaped radiator of 85.5 $\Omega$ for better impedance matching. The proposed ACS-fed antenna has a small physical footprint with dimensions of 0.6$\lambda$ × 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 $\lambda$ 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.

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
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 (0.02λ) 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 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
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.

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 $1.0\lambda \times 1.6\lambda$ at 28GHz. The antenna topology is symmetrical about the Y-axis. Schematics of the proposed 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

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**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 mm²), GB = Gain bandwidth, FTBR = Front-to-back ratio (in dB), NA = Not available, CPS = Coplanar stripline, PW = Proposed work.
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.

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
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.

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 $-45^\circ$ to $+45^\circ$ is attained over the entire operating band. Shared ground module directs beam at $\pm 30^\circ$ and the central
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.

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