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A Wideband Conformal Antenna with High Pattern Integrity for mmWave 5G Smartphones

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Abstract—In this paper, a co-planar waveguide fed circular slot antenna with an operational impedance bandwidth of 20–28 GHz is proposed. In order to reduce the effective occupied volume when the antenna is integrated onto a typical mmWave 5G smartphone, a conformal topology is investigated. Since the radiating aperture is not backed by an electrically large ground plane, it leads to a bidirectional beam resulting in an inherently low forward gain of 4 dBi with a front to back ratio of 1 dB. Hence, a compact exponentially tapered copper film reflector is integrated electrically close (0.046λ at 28 GHz) to the radiating aperture to achieve a forward gain of 8–9 dBi with an effective radiating volume of $0.24\lambda^3$. The impedance bandwidth is from 25 to 30 GHz (18.2%) with a 1-dB gain bandwidth of 34.7% indicating high pattern integrity across the band. Since the proposed antenna element offers wideband with high gain, it is a potential candidate for mmWave 5G smartphones.

1. INTRODUCTION

The phenomenal growth in the smartphone users over the years has provoked researchers in academia and industry to design future-proof transceivers facilitating high data-rates, which in turn need high carrier frequencies, such as 28 GHz band. The 28 GHz band is projected as a potential candidate for future 5G cellular communication systems. The fundamental challenge for deployment of 28 GHz radios is the inherent high path loss. It must also be noted that the penetration losses for common building materials are in the range of 20–40 dB [1]. Researchers have proposed and demonstrated the application of phased arrays to realize high gain with beam steering at both the base station and the mobile terminals [2]. The beam locking sequence becomes intricate in a dynamic environment. Phased arrays also suffer from scanning loss when the beam is steered away from the boresight [3, 4]. The desirable features of mmWave antennas targeting smartphone applications must have: least physical footprint with high gain for the available radiating aperture, wide impedance bandwidth, and low SAR values post-integration of the antenna with the smartphone. The designs proposed in [5–9] offer wideband with low pattern integrity across the band leading to variation in gain. The conformal antennas of [10, 11] have low gain yield for the available aperture. Also, most of the antennas in reported articles operating at 28 GHz are planar. Hence, a conformal antenna with higher gain yield with minimal physical footprint is investigated in this paper.

2. ANTENNA DESIGNS

The schematic of the proposed CPW-fed wideband mmWave antenna is illustrated in Figure 1(a). It is designed on a Nelco NY9220 substrate with relative dielectric constant of 2.2, loss tangent of 0.0009, and thickness of 508 μm. The CPW feed-line width and the gap were chosen to accommodate the end-launch connector and to prevent additional radiation due to an over-moded antenna element. Since the

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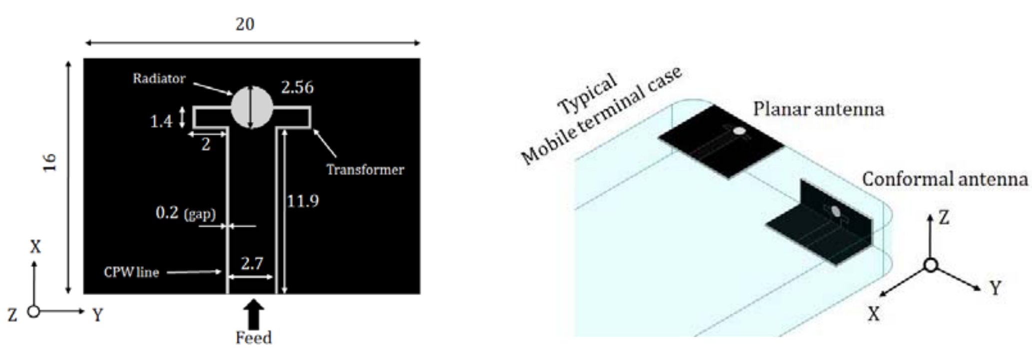
feed-line with width of 2.7 mm and gap of 0.2 mm leads to a characteristic impedance of 59 Ω, a stepped impedance transformer of 50 Ω was utilized as an impedance transformer to the radiating circular slot of 80 Ω, which results in an input impedance of 65 Ω leading to input reflection coefficient less than −10 dB. Since the circular slot is uniformly illuminated independent of the frequency, a wide impedance bandwidth is achieved. The impedance bandwidth of the planar element is from 20 to 28 GHz (30%). In order to minimize the effects of the electrically large end-launch connector, the slot radiator was placed 1λ away from the feed point [3].

The radiation is in both sides of the element, since the antenna is not backed by an electrically large ground plane. Even though the antenna exhibits high pattern integrity, the front to back ratio is close to 0 dB throughout the band consequently leading to a gain of 2–3 dBi, which might not be suitable for integration in mmWave 5G smartphone that has requirements of high gain with minimal radiation towards the user. The designed CPW-fed antenna is planar, leading to a poor gain for the available radiating aperture of the smartphone. Hence, a 90° bend is introduced to make it conformal. The choice of the substrate with low loss tangent and thickness is evident here. Even though PET films or polycarbonate substrates are more flexible than Nelco NY9220, the loss tangent is high, hence leading to a lossy radiator resulting in poor gain especially at mmWave frequencies [12]. A 508 μm thick substrate is an optimal choice for corner bending as it does not require additional scaffolding [13], and thicker substrates would lead to a design with piecewise construction resulting in higher discontinuity causing additional impedance mismatch. The impedance bandwidth of the conformal antenna is from 28.5 to 33.5 GHz (16.2%), and the shift in the operational band is primarily because of the discontinuity introduced due to the 90° bending. The conformal antenna suffers from bidirectional radiation as it is not backed by a conductor, but the front to back ratio is improved to 1 dB across the band due to the orthogonal ground plane. The forward gain of the conformal antenna is 4–5.6 dBi [11]. Figure 1(b) illustrates the comparison of planar and its conformal counterpart. It is evident from the illustration that the physical footprint of the antenna has reduced post conforming, which in turn saves space for RF real estate.



(a) (b)

Figure 1. (a) Proposed planar antenna (All dimensions are in mm). (b) Comparison of planar and conformal antennas.

Thus, in order to improve gain and also reduce the back radiation towards the user, an exponentially tapered reflector is integrated with the conformal radiator as shown in Figure 2. The simplest solution to achieve unidirectional radiation is to back the slot radiator with an electrically large copper flat plate at 0.25λ (2.5 mm away from the radiator), and this method would yield a lower bandwidth and poor gain yield in addition to detuning the antenna element due to higher coupling of the feed line and all-metallic plate. Hence, an exponentially tapered copper film is designed at a distance of 0.046λ from the slot radiator. A 3D printed scaffolding was designed and fabricated using a Raise 3D RxP2200 3D printer with a surface roughness close to ±150 μm and polylactic acid (PLA) material with a dielectric constant of 2.75. The contour of the 3D printed scaffolding was optimized for high gain and wideband for an electrically close design. A thin copper film of thickness 75 μm was carefully pasted onto the 3D printed scaffolding to realize the exponentially tapered reflector. The height of the reflector was

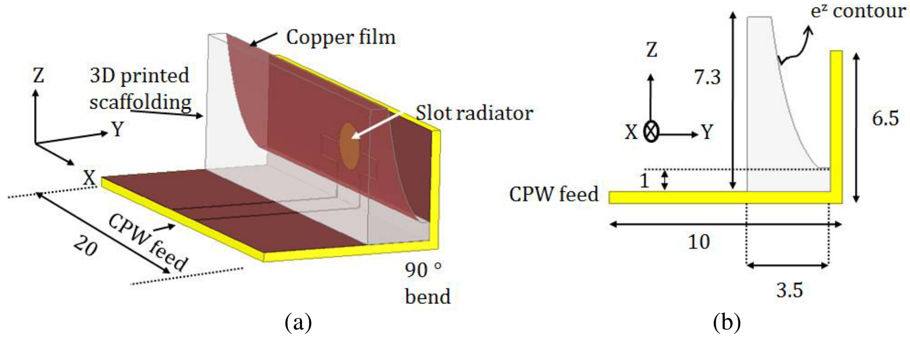


Figure 2. Schematic of the proposed conformal antenna. (a) Isometric view. (b) Side view.

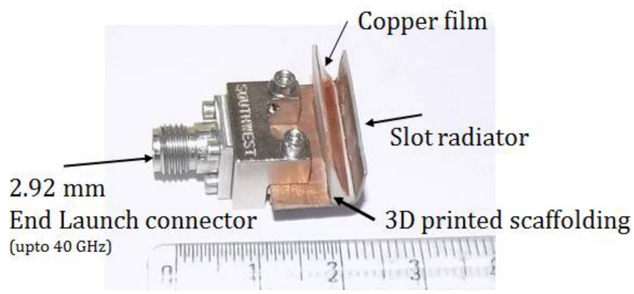


Figure 3. Photograph of the fabricated prototype.

optimized to fit inside a typical smartphone casing, and it must also be observed that the reflector has a clearance of 1 mm from the feed plane to minimize coupling between feed and reflector. A photograph of the fabricated prototype is illustrated in Figure 3.

3. RESULTS AND DISCUSSIONS

The simulated and measured input reflection coefficients of the proposed conformal antenna backed by an exponentially tapered reflector are depicted in Figure 4. It is observed that the impedance bandwidth is from 27 to 32 GHz (17%) when the slot radiator is backed by the metallic exponentially tapered reflector alone. However, the copper reflector cannot be suspended in air for the specified dimensions. Styrofoam would have been an ideal candidate for the design of the scaffolding, but the contour requires precise dimensions which would be challenging to achieve with the fragile Styrofoam. Hence low-cost lossy substrate PLA with a dielectric constant of 2.9 and loss tangent of 0.01 was used to realize a sturdy scaffolding. The impedance bandwidth detunes to 25–30 GHz (18.2%) primarily due to the coupling of the dielectric 3D printed scaffolding with the CPW feed-line, which is inevitable in the given context. The detuning and bandwidth reduction effects could be mitigated by using substrates compatible with 3D printing with very low dielectric constant (close to 1) and low dielectric loss tangent (less than 0.0001). The bandwidth could be further enhanced by increasing the radiating volume between the slot radiator and the reflector with a compromise in the physical footprint and forward gain in accordance with the gain-bandwidth principle [14]. The discrepancy between the simulated and measured curves is due to the non-ideal solder-less transition between the end-launch connector and the fabricated antenna element. All the simulations were performed in Ansys HFSS, and the corresponding S parameter measurements were performed with Agilent PNA E8364C.

The 3D patterns with and without the reflector at 28 GHz are shown in Figure 5(a). The E-field plots confirm the action of the exponentially tapered reflector as observed in Figure 5(b). It is evident that the reflector is effective in improvement in the front to back ratio, consequently leading to an

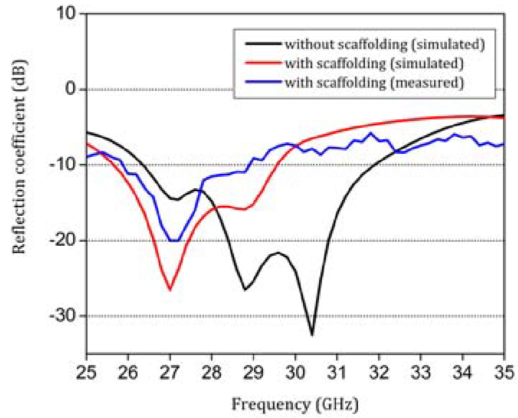


Figure 4. $|S_{11}|$ of the conformal antenna.

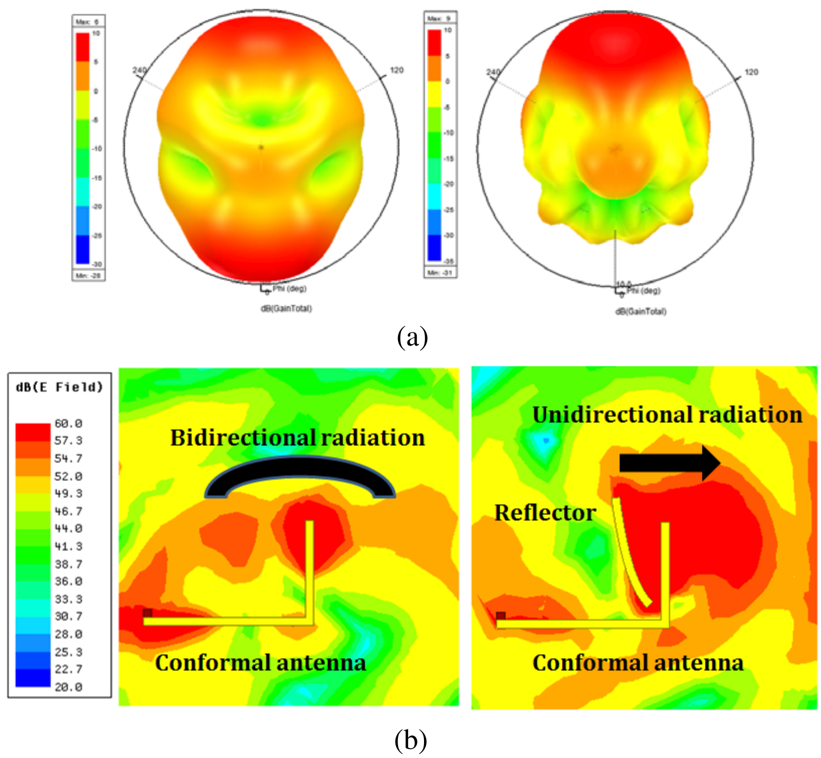


Figure 5. (a) 3D patterns without and with reflector. (b) E-field plots without and with reflector.

enhancement of forward gain. The radiation patterns are illustrated in Figure 6, and the beamwidth in YZ plane (E-plane) is $65^\circ \pm 3^\circ$ and in XY plane (H-plane) is $55^\circ \pm 5^\circ$, with a front to back ratio of more than 12 dB across the band. Since the beamwidth variation is minimal in both the principal planes, the pattern integrity is pretty high. The forward gain is shown in Figure 7. The gain varies between 8 and 9 dBi across the band 25–35.5 GHz (34.7%) indicating a high gain yield for an effective radiating volume of $0.24\lambda^3$ at 28 GHz. The figure also demonstrates the forward gain when the slot radiator is backed by a conventional metal reflector at 0.25λ, which results in poor gain-bandwidth. The gain could be further increased by increasing the height of the reflector, but this would compromise the physical footprint of the antenna.

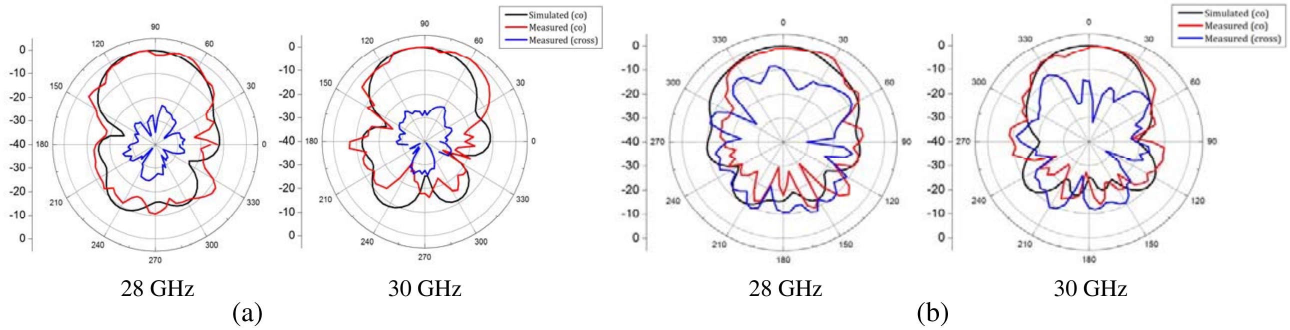


Figure 6. Radiation patterns at 28 and 30 GHz in (a) YZ plane (b) XY plane.

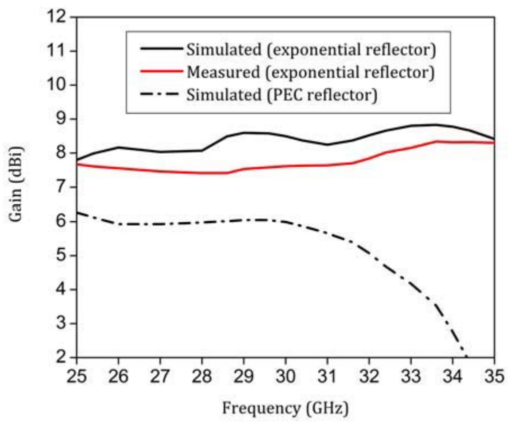


Figure 7. Forward gain of the conformal antenna.

Table 1. Comparison with other designs.

Ref	F	IBW	G	GBW	ERV	Feed	Conformal
[3]	28	36.2	6	24.2	0.01	Microstrip	No
[4]	28	43	9	24.6	0.138	SIW	No
[5]	60	23.7	11	11.6	0.716	Microstrip	No
[6]	60	11.6	12	11.6	1.09	Microstrip	No
[7]	60	11.6	20	21.8	68.64	Microstrip	No
[8]	64	14.6	11	6.1	0.08	Microstrip	No
[9]	28	18.2	11	10.9	0.05	Microstrip	No
[1]	28	18	6.5	32	0.32	CPW	Yes
[11]	28	17	7	33.4	0.27	CPW	Yes
Proposed	**28**	**18.2**	**9**	**34.7**	**0.24**	**CPW**	**Yes**

Ref = Reference, F = Centre frequency (GHz), IBW = 10-dB impedance Bandwidth (%),
G = Gain (dBi), GBW = 1-dB Gain Bandwidth (%), ERV = Effective Radiating Volume (λ^3)

Table 1 illustrates the advantages of the proposed element compared to previously reported designs.

4. CONCLUSION

A CPW-fed circular slot antenna is proposed to operate in the 28 GHz band. A conformal topology is investigated leading to bidirectional radiation. Hence, an exponentially tapered reflector is integrated electrically close to the slot radiator, leading to an impedance bandwidth from 25 to 30 GHz (18.2%) with a front to back ratio of more than 10 dB across the band. The forward gain of the conformal antenna is 8–9 dBi, and a 1-dB gain bandwidth of 34.7% indicates a high gain yield for the available aperture. Thus, the proposed antenna is a suitable candidate for future mmWave 5G smartphones.

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