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RESEARCH ARTICLE

A mmWave Low Complexity and Low-Cost Super Wideband Dual-Polarized Aperture Coupled Antenna for 5G Applications

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ABSTRACT Advanced antenna system (AAS) is a viable option for 5G millimeter-wave (mmWave) applications. AAS single element is favored to be dual-polarized, wideband, high gain, and compact in order to be utilized for 5G antenna arrays. In this paper, a low complexity and low-cost, dual-polarized aperture coupled antenna operating from 24 up to 44 GHz is presented for 5G mmWave applications. A design methodology is developed to innovate the aperture-coupled antenna in mmWave frequencies upgrading with dual-polarized configuration and grid-slotted technique to meet the AAS single-element requirements. The antenna has an overall size of 0.56 $\boldsymbol{\lambda_0}\times$ 0.56 $\boldsymbol{\lambda_0}$ while the radiating patch si-ze is only 0.39 $\boldsymbol{\lambda_0}\times$ 0.39 $\boldsymbol{\lambda_0}$ at the lower frequency of the operating band, a wide bandwidth of around 60%, and polarization isolation of better than 35 dB, a promising radiation characteristics with the polarization discrimination of more than 20 dB and average gain of 7dBi at 5G mmWave bands. The performance comparison shows the advantages and novelty of the proposed antenna in terms of bandwidth and gain with a low complexity and low-cost structure compared to the most recent relevant publications. To the author's knowledge, there has been no mmWave aperture-coupled antenna reported in literature with such great performance and simple structure. The proposed antenna element is a suitable candidate as a part of massive MIMO systems for 5G n257, n258, n259, n260, and n261 frequency bands.

INDEX TERMS Advanced antenna system, aperture coupled antenna, 5G antennas, 5G array, mmWave antenna, massive MIMO.

I. INTRODUCTION

Millimeter wave (mmWave) frequencies have seen a rapid growth of interest in the fifth generation of mobile communication (5G) due to the wide available bandwidth and massive data rates. Antennas operating in the mmWave frequencies need to address wide bandwidth and high gain. Advanced antenna system (AAS) is introduced as an essential part of the mmWave 5G systems to improve capacity and coverage performances. AAS utilizes novel techniques e.g. Multiple Input Multiple Output (MIMO), adaptive beamforming, and Space Division Multiple Access (SDMA) aiming at improving the performance and spectral efficiency of 5G transceivers. AAS technical requirements for 5G applications are recommended in terms of antenna element properties, array structures, and beamforming characteristics [1].

The single-element antenna for AAS is suggested to possess ±45°dual-polarization and the 3 dB beam width of at least 65° and to be inline with 3GPP mmWave bands: n258, n257, n261, n260, and n259 ranging from 24.25 GHz to 43.5 GHz as [2] and [3]:

n258: 24.25 GHz – 27.5 GHz
n257: 26.5 GHz – 29.5 GHz
n261(subset of n257): 27.5 GHz – 28.35 GHz
n260: 37 GHz – 40 GHz
n259: 39.5 GHz – 43.5 GHz

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Aperture coupled antenna can be a good candidate for the AAS single element due to its large bandwidth, low profile, and low-cost features, separate feed layer and easy integration, excellent cross polarization, and efficiency compared to conventional microstrip antennas.

The basic aperture-coupled microstrip antenna consists of a top substrate layer for radiating microstrip patch element and a bottom substrate layer for the microstrip feed line. The electromagnetic power is coupled through the aperture in the ground plane [4]. The dual linearly polarized configuration can be designed by coupling the patch to two microstrip lines via two orthogonal slots in the ground plane [5]. Various slot shapes were proposed to improve the bandwidth and isolation of the dual-polarized aperture-coupled antennas [6], [7], [8].

In recent years, several aperture-fed antennas for mmWave bands have been reported. In [9], a wideband cross-slot aperture-fed antenna is presented for mmWave 5G applications. The double-layered antenna element with an overall size of 14 × 15 mm^2 provides an impedance bandwidth of 31.40% (25.5 – 35 GHz), circular polarization for 26.20 - 34.16 GHz, and a gain of 5.6 ± 1dBic. A wideband circularly-polarized aperture coupled magneto-electric dipole is presented in [10] for mmWave applications. The impedance bandwidth is 50% (21- 35 GHz), while the 3 dB AR bandwidth is 40.9% (22.2 - 33.6 GHz) with a variation gain between 6.1 and 8 dBi.

A very wide band mmWave antenna with 60% bandwidth is designed in [11] but with a single polarization. Achieving large bandwidth with dual-polarized configuration is associated with complex and bulky structures [12]. In [13], a dual-polarized aperture coupled and stripline-fed antenna is presented operating from 24 up to 40 GHz for 5G mmWave applications. A seven-substrate layered stacking arrangement of ring patches is proposed to achieve wide bandwidth with stable gain. However, the antenna structure is complex and the gain is between 4 – 5 dBi. As can be seen, most of the published aperture-fed antennas in mmWave frequencies despite their complex structures cannot satisfy the requirements of the antenna element suitable for 5G AAS.

On the other hand, in [14], [15], and [16], grid-slotted patch is reported as a broadband impedance matching technique in a single-polarized aperture coupled feed antenna structure in microwave frequencies. Nonetheless, the grid-slotted technique is not evolved accordingly in mmWave frequencies and dual-polarization configuration.

In this paper, a novel and low complexity super wideband dual-polarized aperture coupled antenna element with high gain and compact size is developed in mmWave frequencies to satisfy the 5G AAS requirements. The design methodology innovates the conventional aperture-coupled antenna in mmWave frequencies upgrading with dual-polarized configuration and metasurface based grid-slotted technique to meet the AAS single-element requirements. A comparison between the proposed antenna and related works approves the novelties and advantages of the design.

II. DUAL-POLARIZED APERTURE COUPLED ANTENNA DESIGN

The geometry of the proposed dual-polarized stacked patch antenna is depicted in Fig. 1. The antenna comprises a stacked patch, two microstrip feed lines, and two slots on the ground plane.

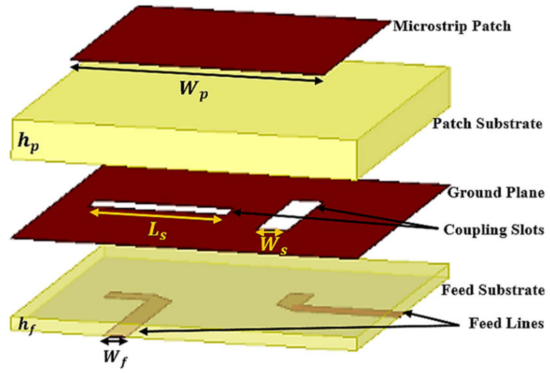

FIGURE 1. Dual-polarized aperture coupled microstrip antenna.

It can be stated that slim thick microstrip substrates exhibit less spurious radiation from feed lines but higher loss while thicker substrates provide wider bandwidth, but less coupling for a given aperture size [17]. A tradeoff compromise should be applied for substrate thickness.

Low-loss electrically thin feed substrate ($< \lambda/50$) with a high dielectric constant is recommended while for patch substrate low-loss electrically thin ($< \lambda/10$) with a low dielectric constant is preferred [18].

For this design, the dielectric substrate used is Rogers 4350B ($\varepsilon_r = 3.48$) as a very popular substrate for mmWave design with medium dielectric constant for both substrates with different thicknesses as:

$$\text{Feed substrate}(< \lambda/50) \approx 0.25mm \rightarrow h_f = 0.254mm \tag{1}$$

$$\text{Patch substrate}(< \lambda/10) \approx< 1.25mm \rightarrow h_p = 0.761mm \tag{2}$$

where wavelength corresponds to the minimum design frequency $f = 24$ GHz.

The design starts with defining the width of the microstrip feed line. As there are two layers, the width of the feed line can be properly selected using the strip line equation as [19]:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} ln\left(\frac{1.9(h_f + h_p + t)}{0.8w_f + t}\right) \rightarrow w_f \approx 0.48\ mm \tag{3}$$

where $Z_0 = 50\Omega$ is the characteristic impedance, $h$is the substrate thickness and t is the strip thickness.

The next step is determining the slot length and width. The slot length affects the coupling level along with back radiation. Therefore, the slot length should be selected in accordance with the proper impedance matching. The slot width also influences slightly the coupling level. The slot width is typically 0.1 slot length [17]. The slot length can be selected in the range of 0.1 λ to 0.2 λ ($f = 24$ GHz):

$$\text{Slot length: } L_s = 0.2\lambda = 2.5\ mm \tag{4}$$

$$\text{Slot width: } W_s = 0.1L_s = 0.25\ mm \tag{5}$$

The patch width determines the resonant frequency of the antenna [3].

$$W_p = \frac{\lambda}{2\sqrt[4]{\varepsilon_r}} \approx 4.8\ mm \tag{6}$$

where wavelength corresponds to the minimum design frequency $f = 24$ GHz.

Dual-polarized configuration can be obtained by cutting two orthogonal slots in the ground plane, each of which excites the patch with a different linear polarization. Two orthogonal modes can be excited by two cross-symmetric feed lines. The microstrip feed line with an open stub improves the matching and front-to-back ratio. The feed line is placed at the center and right angle of the slot for maximum coupling and minimum backward radiation.

The antenna is modeled, simulated, and optimized using the Ansys HFSS simulator package. Fig. 2 shows the simulated reflection coefficient of the single-polarized conventional aperture coupled antenna with the initial designed parameters.

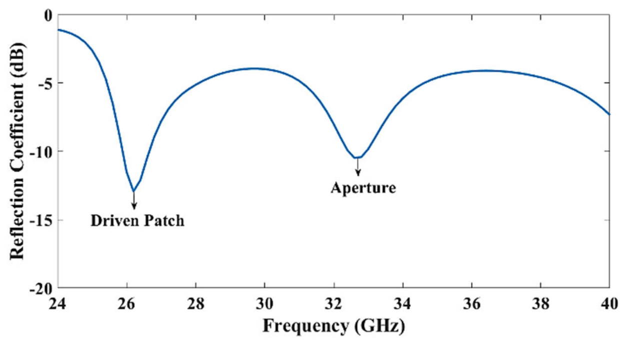

FIGURE 2. Simulated S_{11} for initially designed aperture coupled microstrip antenna.

As can be seen, the first and second resonance frequencies are as a result of the driven patch and slot length respectively. Moreover, the weak point of the aperture-coupled antenna particularly in mmWave frequencies is the low operational bandwidth. As a result, novel techniques should be employed to improve the bandwidth.

In this work, the radiating patch is slotted as a grid to improve the impedance bandwidth significantly. The gap between the slots is chosen as small as 0.01λ (∼ 0.12 mm). The effect of metasurface-based grid-slotted compared to the simple patch is investigated via the model shown in Fig. 3 using full-wave numerical analysis. The simulation results are presented in Fig. 4 depicting the magnitude and phase of S-parameters of both structures.

The results show that the grid-slotted patch can improve significantly transmission power for the frequencies

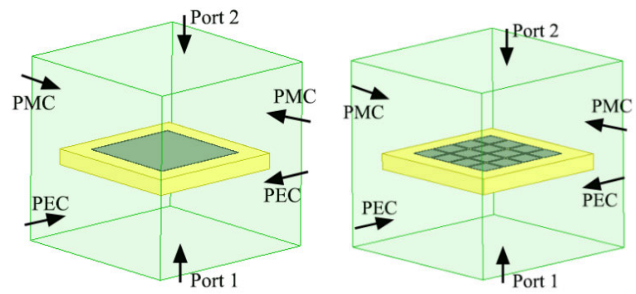

FIGURE 3. Simulated model of the simple and grid-slotted patch.

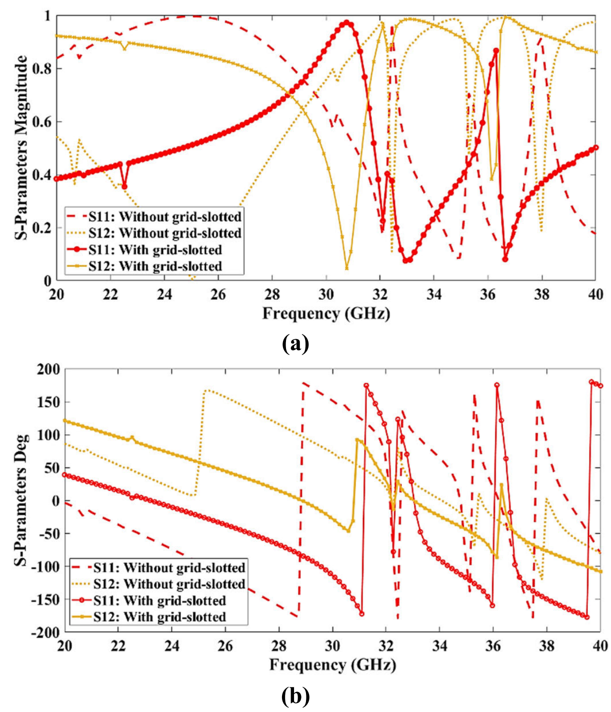

FIGURE 4. Simulated S-Parameters of the simple and grid-slotted patch (a) S-Parameter Magnitude, (b) S-Parameter Phase.

below 30 GHz compared to the simple patch and therefore most of the radiation power can be transmitted through the grid-slotted patch within the wide frequency band.

The comparison between the regular and grid-slotted patch for the aperture-coupled antenna with the initially designed parameter is presented in Fig. 5 and clearly shows that a grid-slotted patch improves the bandwidth between the resonant frequencies.

A parametric study has been conducted to consider the effect of slot width, slot length, and grid-slotted gap on S-parameters as shown in Fig. 6.

The results show that the impedance is low for the slot width < 0.4 mm and the slot width > 0.8 mm provides good impedance matching but with limited bandwidth and higher mutual coupling. The slot width of around $0.1\lambda_g$ (0.6 mm) accommodates impedance matching in a wide bandwidth with mutual coupling<−30 dB. The analysis of slot length demonstrates that increasing the slot length decreases the

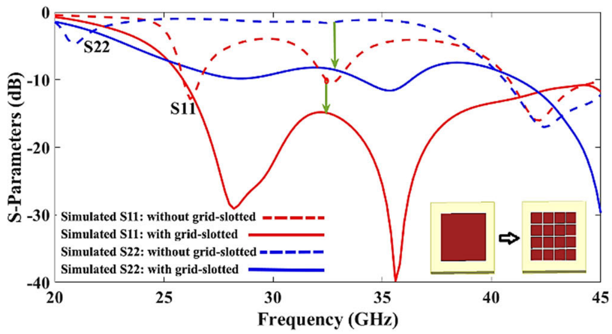

FIGURE 5. Comparison between regular patch and grid-slotted patch.

aperture resonance frequency and increases the mutual coupling. The slot length of around $0.4\lambda_g$ (2.6 mm) exhibits the widest bandwidth across the target frequency band.

A lower grid-slotted gap leads to lower resonance frequency and bandwidth while the gap length of around $0.02\lambda_g$ (0.12 mm) provides the maximum bandwidth for the target frequency band.

The parameters of the proposed aperture coupled antenna are optimized aiming for a super wide bandwidth covering 24 – 43.5 GHz to support *n257*, *n258*, *n259*, *n260*, and *n261* 5G frequency bands and maximum possible broadside gain with the minimum back lobe. The structure of the proposed dual-polarized aperture coupled antenna is illustrated in Fig. 7. Four holes are created on four sides of the two layers (Fig. 7c) for manual alignment of the whole structure using injected glue. The commercial 2.92 mm connector is exploited for antenna testing. The antenna parameters have been summarized in Table 1.

TABLE 1. Proposed aperture coupled antenna parameters.

Parameter	W	W_p	g	W_f	W_s	L_S
Size (mm)	7	4.9	0.12	0.5	0.6	2.53
Parameter	L_H	L_V	L_{O1}	L_{O2}	S_1	S_2
Size (mm)	2.25	3.3	0.91	0.8	2.2	0.7

The prototyping of the proposed antenna with dimension sizes illustrated in Table 1 is realized by fabricating two substrate layers separately and then aligning them manually through the exact embedded holes and strong glue. Two commercial 2.92 mm connectors are mounted to the H and V polarization feed lines. The fabricated antenna is shown in Fig. 8.

Fig. 9 presents the simulated and measured S-parameters for the frequency range 20 – 45 GHz. The results show a good −10dB impedance matching and mutual coupling < −35dB for mmWave 5G frequencies ranging from 24 to 44 GHz. However, the fluctuations with the measured reflection coefficients need to be considered. To this effect, the influence

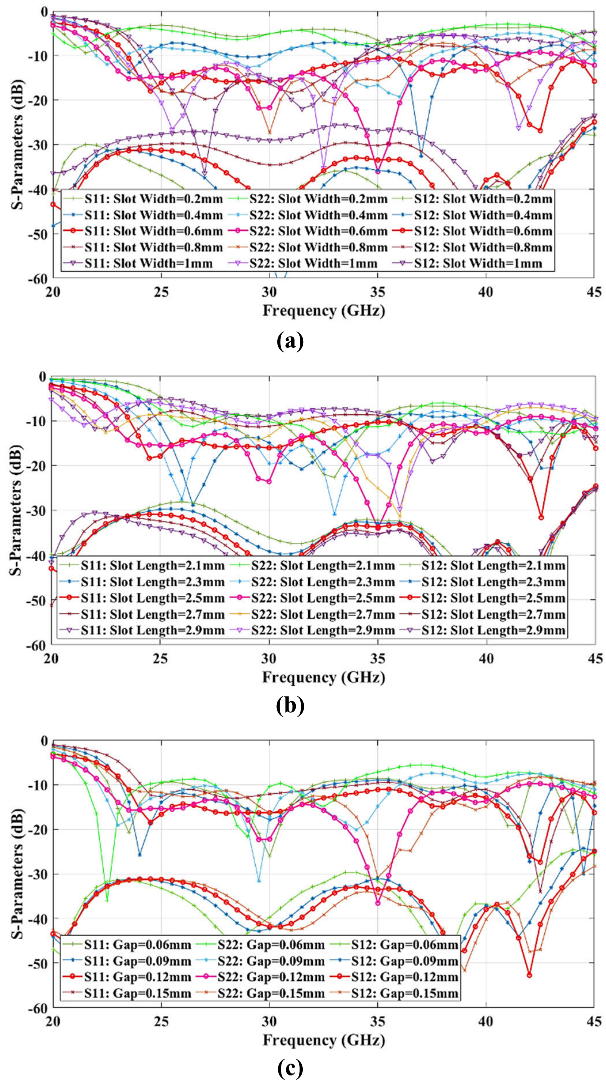

FIGURE 6. Simulated S-parameters for different parameters (a) slot width, (b) slot length, (c) grid-slotted patch.

of the estimated misalignment of the two substrates and connectors as well as the soldering are simulated. The slight misalignments move the resonance frequencies while the soldering may behave as a stub and create resonance fluctuations. Fig. 10 shows the simulated S-parameters with a soldering example indicated in the figure and justifies the measured results.

The vector current distribution on the ground plane is depicted in Fig. 11 when horizontal and vertical ports are excited separately and the other port is terminated. By exciting the horizontal port, the figure of current around the horizontal slot gives rise to the coupling of power through the slot to the driven patch. Moreover, the intensity of the currents around the vertical slot is more than 30 dB lower compared to the currents around the horizontal slot. Also, the currents around the vertical slot are in the same direction which will eliminate each other in the edge. Consequently, high isolation

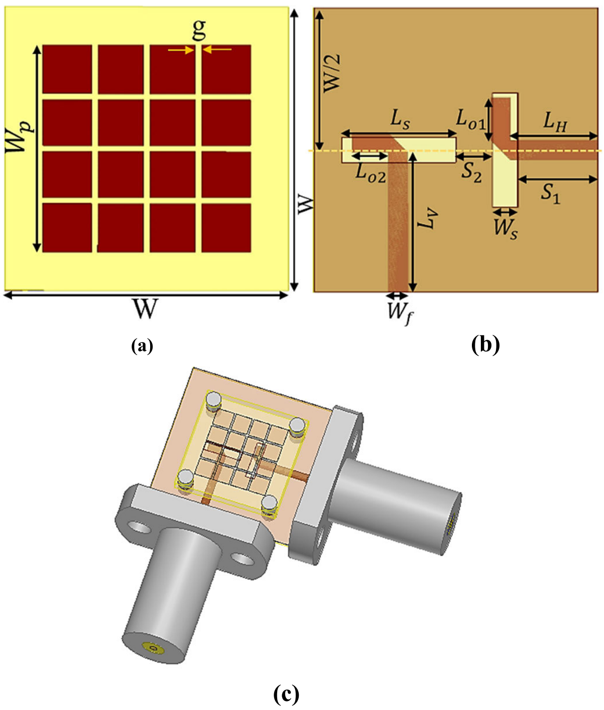

FIGURE 7. Structure of the proposed aperture-coupled antenna. (a) Radiation layer. (b) Feed layer. (c) Complete structure with 2.92 mm connectors.

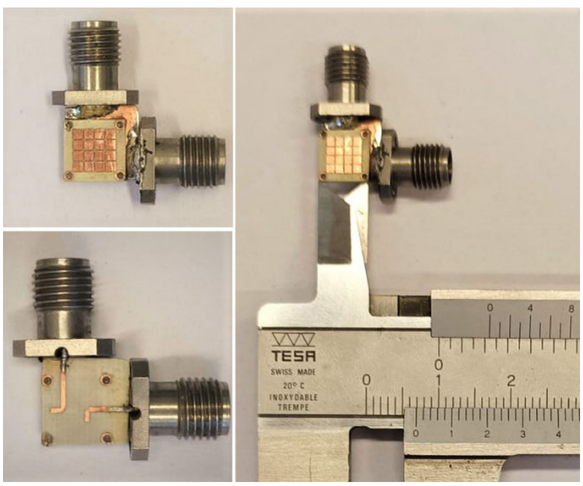

FIGURE 8. Fabricated aperture coupled antenna.

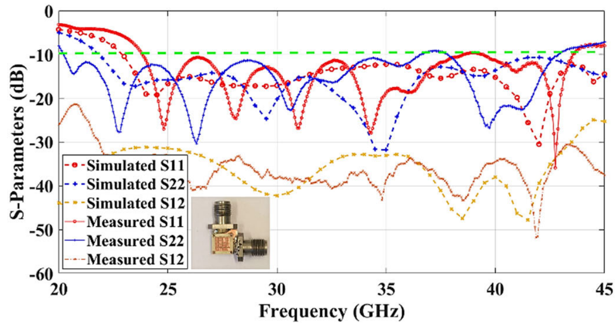

FIGURE 9. Simulated and measured S-parameters for the proposed antenna.

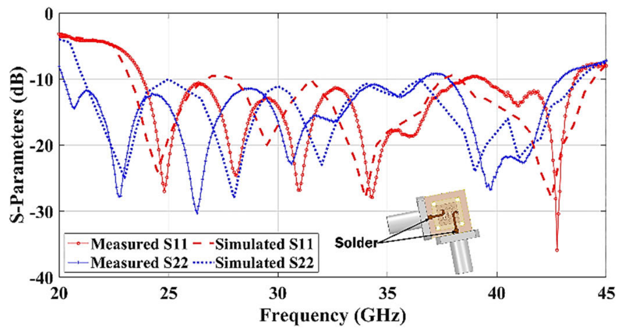

FIGURE 10. Simulated and measured S-parameters for the proposed antenna with soldering effect.

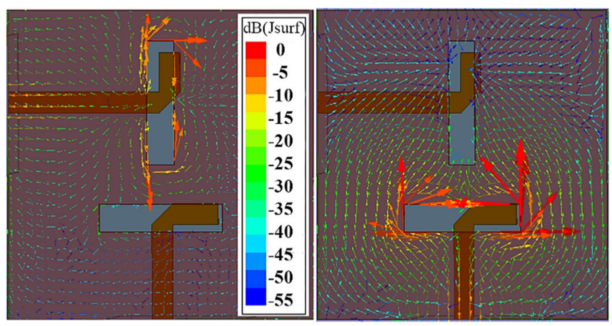

FIGURE 11. Vector current distribution on the ground plane for horizontal and vertical ports.

between the ports can be achieved. A similar deduction can be considered for exciting the vertical port.

To consider the radiation characteristics, the simulated and measured radiation patterns in the E and H planes for both co and cross-polarization are shown in Fig. 12 for some selected frequencies inside the bandwidth. Also, Fig. 13 presents the simulated and measured antenna gains for both polarizations. A termination load presented in [20] is exploited to terminate the unused port in the measurement process.

It can be found that the antenna has broadside radiation with a 3 dB beam width of at least 65° which satisfies the requirements for AAS single-element. The radiation pattern distortion at higher frequencies (36 GHz and 40 GHz) might be due to the effect of the connector. The cross-polarization is greater than 20 dB for all measured frequencies. The average antenna gain is around 7dBi for the target 5G bands.

To reveal the advantages of the research work, a comparison between the proposed and recently published aperture-fed antenna elements for 5G mmWave application is summarized in Table 2 in terms of structure and performance. It can be observed that the fabricated antenna in this work is characterized by a very wide bandwidth, high gain, compact size, low complexity and low-cost, and dual polarization capability that can satisfy the AAS requirements.

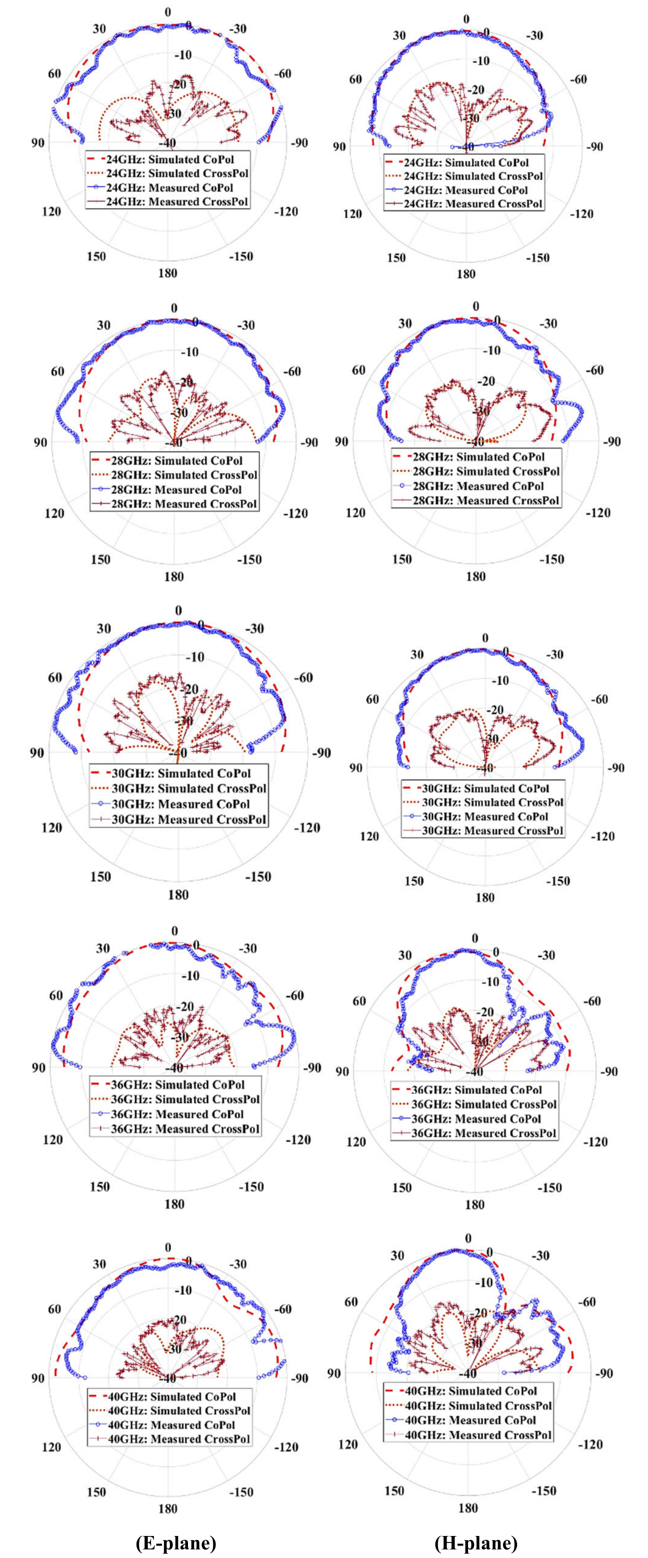

FIGURE 12. Simulated and measured normalized radiation patterns (dB).

As compared with dual-polarized antennas in [12] and [13], the proposed antenna exhibits wider bandwidth and higher gain which is realized by only two substrate layers which reduces the complexity and fabrication cost significantly. In addition, the overall size of the antenna is 0.56 $\lambda_0 \times$ 0.56 λ_0 while the size of the radiating patch is only 0.39 $\lambda_0 \times$ 0.39 λ_0 which is favorable for array applications.

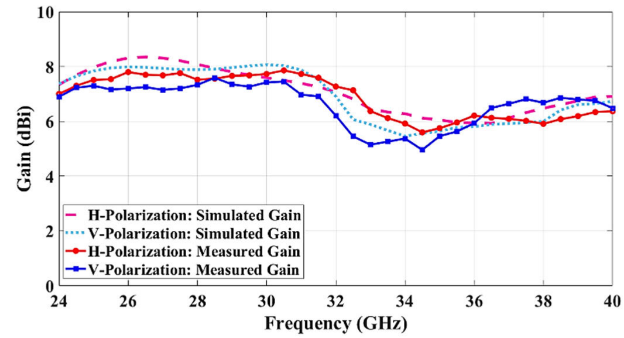

FIGURE 13. Simulated and measured broadside gain.

TABLE 2. Comparison of the proposed design with state-of-the-art aperture-fed antennas for 5G mmWave applications.

Reference	Layers	Polarization	Freq. Band (GHz)	Av.Gain (dBi)	Size (λ_0)
[9]	2	Circular	25.5 - 35	5.6	1.19 × 1.27
[10]	2	Circular	21 - 35	7	0.84 × 0.52
[11]	2	Single	23.5 - 44	7	0.4 × 0.72
[12]	5	Dual	24.25 – 29.5	5.2	0.63 × 0.63
[13]	7	Dual	24.25-29.5 37 - 40	4.5	0.4 × 0.4
This work	**2**	**Dual**	**24 – 44**	**7**	**0.56 × 0.56**

III. CONCLUSION

5G systems need to utilize AAS to reach full 5G experiences in mmWave bands. The antenna element for 5G AAS is recommended to be dual-polarized, low profile, high gain, and wideband covering 3GPP harmonized frequency bands. In this letter, a novel aperture-coupled antenna is presented to satisfy the AAS requirements for 5G applications. With standard PCB technology, the two-layered low-cost prototype has been fabricated and measured. The results show a large impedance bandwidth of around 60% between 24 – 44 GHz supporting n257, n258, n259, n260, and n261 frequency bands and an average broadside gain of 7 dBi. The antenna has an overall compact dimension of $7 \times 7 \times 0.254$ mm^3. The separate feeding network layer facilitates the integration of the antenna with electronic circuitry very easily. To illustrate the merits of the proposed antenna, a performance comparison is provided with the most recent aperture-fed antennas. The simplicity in structure, low cost in fabrication, dual-polarized configuration, super wide bandwidth, compact size, high gain, high isolation, and high polarization discrimination are the coincident superior performances of the proposed antenna compared to other designs. The antenna element performance satisfies the AAS single element requirements and facilitates developing large antenna arrays using this element to meet 5G massive MIMO applications.

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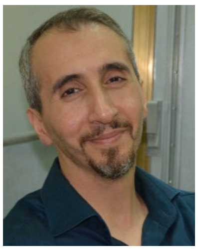

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