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A Novel Low-Profile Broadband Direct-Feed mm-Wave Antenna Array for 5G Smartphone Applications

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Abstract—In this paper, a novel low-profile direct feed antenna element is proposed to work across the mm-wave frequency band for 5G smartphone applications. The antenna covers the frequency band from 25 to 32 GHz achieving a wide fractional bandwidth of 24.5%. Contrary to most of the previously reported designs, the proposed antenna has a low-profile single-substrate structure and uses a conventional corporate feed. To improve the overall gain, a 16-element antenna array is formed based on the proposed antenna element. The total realized gain of the array is 15 dBi, and its size is $63 \times 10 \times 0.64\,\text{mm}^3$ which fits inside a smartphone chassis. To validate the idea, a prototype is fabricated and measured. A study is also conducted, through simulations, on the beam steering capabilities of the antenna array using digital phase shifters. Having a simple structure and good performance makes the proposed antenna array an excellent candidate for 5G smartphone applications.

1. INTRODUCTION

Wireless communication systems have evolved a lot over the last decades. Recently in 2020, wireless communication suppliers have introduced the fifth generation (5G) as the state-of-the-art technology to speed up the data transfer from a source to a destination with a rapid speed that may reach up to 10 GB/sec [1].

This high speed is not reachable by using the common frequencies used in the 3G or 4G wireless communication systems. So, mm-wave is the key feature of the 5G wireless communication system. One of the big challenges that face 5G system designers is that this type of tiny wave does not travel over a long distance. Utilizing robust high gain and broadband antennas is a beneficial solution to improve the communication distance between devices. These devices may be smart handset phones, automotive cars, or even home appliances [2].

Many attempts have been made to design antennas for 5G mobile communications at mm-wave with small size and high gain for smartphones. In [3], an antenna array covers the frequency band from 27.4 to 28.4 GHz with a narrow fractional bandwidth (FBW) of 3.6%. This limited BW does not fulfil the requirements of high-speed 5G communications. In [4], FBW is broadened to be 7.1% covering the frequencies from 27 to 29 GHz with a complex multi-layer structure that does not match smartphones. The authors in [5] introduce an antenna element with a wide frequency band from 26 to 30 GHz (FBW of 14.3%). Unfortunately, the antenna element is designed based on substrate integrated waveguide (SIW) technology which makes it difficult to extend the designed antenna element into an array. In [6], a high gain antenna array is proposed with a simple structure, but the FBW is limited to 4.6% (from 21 to 22 GHz). Later on, in [7], the presented antenna array covers the frequency band from 28 to 32 GHz achieving an FBW of 13.3%. The authors in [8] propose a high gain antenna array with an FBW of

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15.4% covering the frequency band from 24 to 28 GHz. In [9], a 5G miniaturized antenna-in-package is proposed with dual narrow bands for 28 GHz/38 GHz 5G wireless communication. Recently in [10], a mm-wave 3D printed antenna is presented with a broad FBW of 17.5% (from 26 to 31 GHz) at the expense of the antenna size.

In this paper, a novel broadband direct feed mm-wave antenna is proposed. The antenna element has a small size and low profile. The antenna element achieves a realized gain about 4.3 dBi. To improve the overall gain, the antenna element is amended to form a 16-element linear antenna array with a realized gain of 15 dBi. The antenna array covers the frequency band from 25 to 32 GHz achieving an FBW of 24.5%. The array has a simple single-substrate structure with a size of $63 \times 10 \times 0.64\,\text{mm}^3$ which let the whole design fit inside a smartphone chassis. To validate the design, a prototype of the antenna array is fabricated and measured. The antenna array has a narrow half-power beamwidth (HPBW) of 8° along its axis. So, for a practical scenario, a study on beam steering capabilities of the antenna array using digital phase shifters is conducted through simulations to improve the antenna spatial coverage. The results show that the antenna array is able to cover up to 120° with no significant degradation in its performance.

The rest of this paper is organized as follows. Section 2 illustrates the proposed 5G antenna element along with its principles of operation and simulated results. Section 3 discusses simulated and measured results of the proposed antenna array. Section 4 studies the beam steering capabilities of the proposed antenna array, and finally, the paper is concluded in Section 5.

2. PROPOSED 5G ANTENNA ELEMENT

Figure 1 shows the structure of the antenna element. The patch is printed on the top layer of a Rogers RT/duroid 6010LM laminate with a thickness $h = 0.64$ mm, relative permittivity $\varepsilon_r = 10.7$, and a dissipation factor of 0.0023. A full ground plane is printed on the bottom side of the laminate. The copper thickness on both sides is 17.5 µm. The antenna can be simply described as a rectangular patch that lies in the XY plane with a width W_P and length L_P. The rectangular patch was initially designed to have dimensions of $\lambda_g/2$ (where λ_g is the guided wavelength and equals $\lambda_0/\sqrt{\varepsilon_r}$, and λ_0 is the free space wavelength at the central frequency). The patch is fed by a 50 Ω feeding strip. Two identical slits are introduced at both sides of the feeding strip to improve the antenna matching. Each slit has a width W_S and a length L_S. To further improve the antenna matching, a notched slot is cut at the upper edge of the patch. Then, two square cuts are introduced at the lower corners of the patch. The

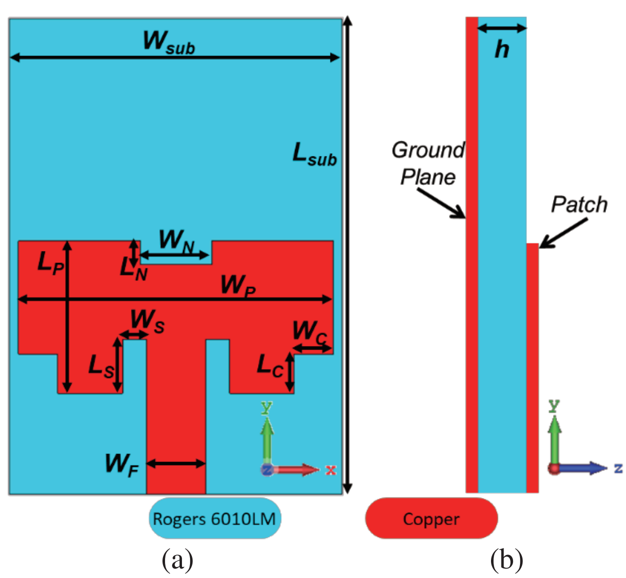
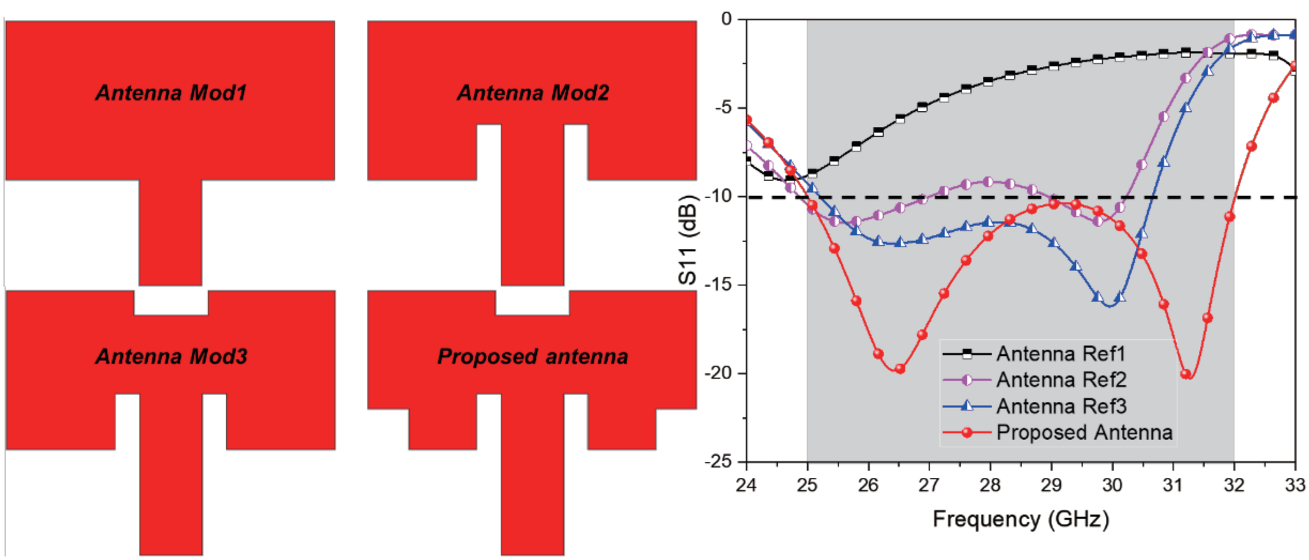


Figure 1. The proposed antenna element (a) front view (b) side view.

dimensions of the patch (in mm) can be summarized as: $W_{sub} = 2.8$, $L_{sub} = 4$, $W_P = 2.65$, $L_P = 1.28$, $W_S = 0.2$, $L_S = 0.45$, $W_C = 0.33$, $L_C = 0.33$, $W_N = 0.6$, $L_N = 0.2$ and $W_F = 0.5$.

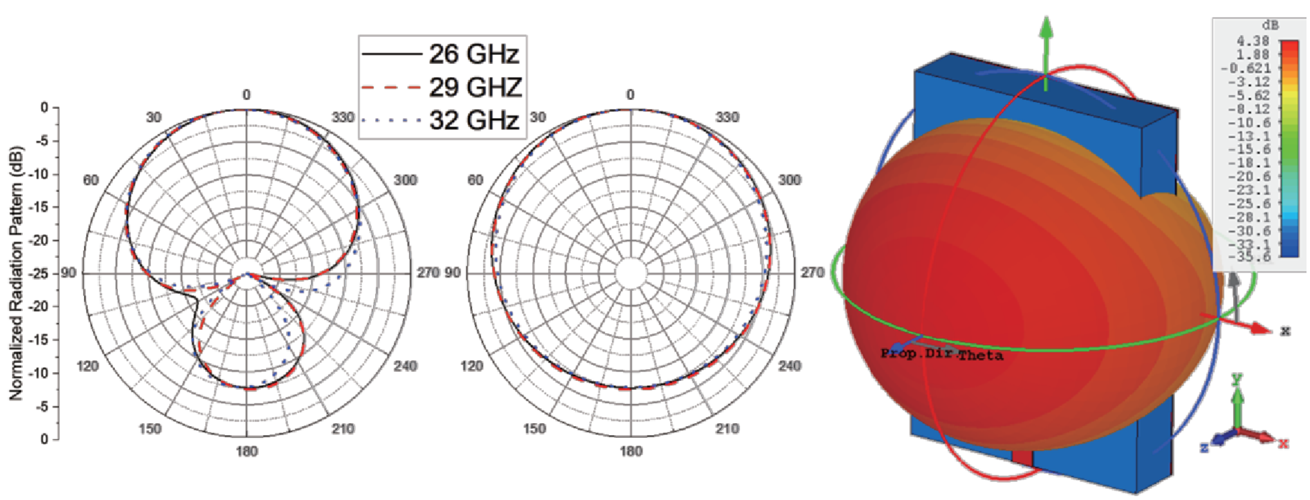
For a better understanding of the working principles of the proposed antenna element, three model designs (antenna Mod1, antenna Mod2 and antenna Mod3) are used as shown in Figure 2(a). Initially, the rectangular patch was designed with no slits, cuts, or slots (antenna Mod1) based on the basic equations for a patch antenna design as in [11]. In this case, the antenna matching is poor, and high return loss is noticed as shown in Figure 2(b). By cutting two identical slits at the opposite sides of the feeding strip (antenna Mod2), the return loss is improved but still not satisfactory. Furthermore, introducing a notched slot (antenna Mod3) significantly improves the return loss. However, the desired frequency band is not fully covered. This is achieved by cutting two square cuts at the bottom corners of the patch (proposed antenna element). In this case, the antenna achieves a return loss of better than 10 dB (VSWR ≤ 2) across the frequency band from 25 to 32 GHz (FBW of 24.5%).

The normalized radiation patterns at the E-plane (YZ-plane) and H-plane (XZ-plane) are shown



(a) (b)

Figure 2. Model and proposed antennas (a) evolution (b) return loss.



(a) (b) (c)

Figure 3. Radiation patterns of the proposed antenna element (a) E-plane (b) H-plane (c) 3D.

in Figures 3(a) and (b) respectively at 25 GHz, 29 GHz, and 32 GHz while the simulated 3D radiation pattern at the central frequency is shown in Figure 3(c). It is evident that the antenna element has a stable radiation pattern across the frequency band with HPBWs of 95.5° and 142° at the E-plane and H-plane, respectively. The antenna realized gain at boresight (Z-axis) is 4.3 ± 0.2 dBi across the frequency band as illustrated in Figure 4. The total efficiency of the proposed antenna element is $92 \pm 3\%$.

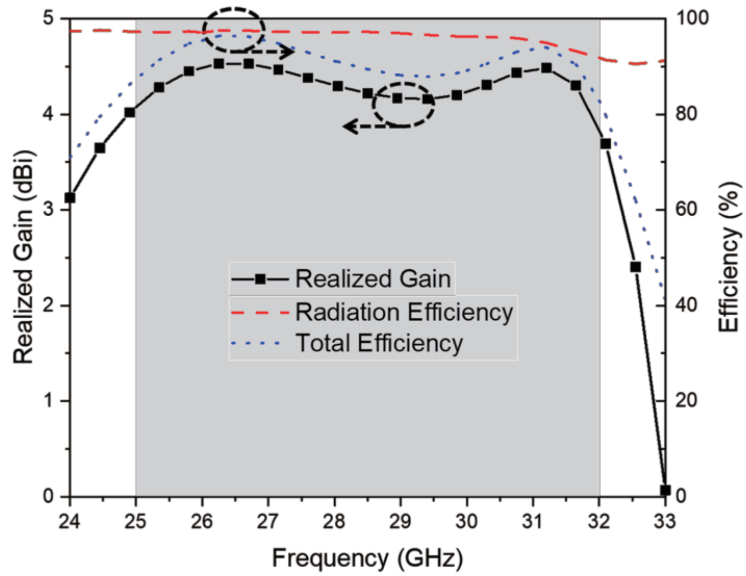
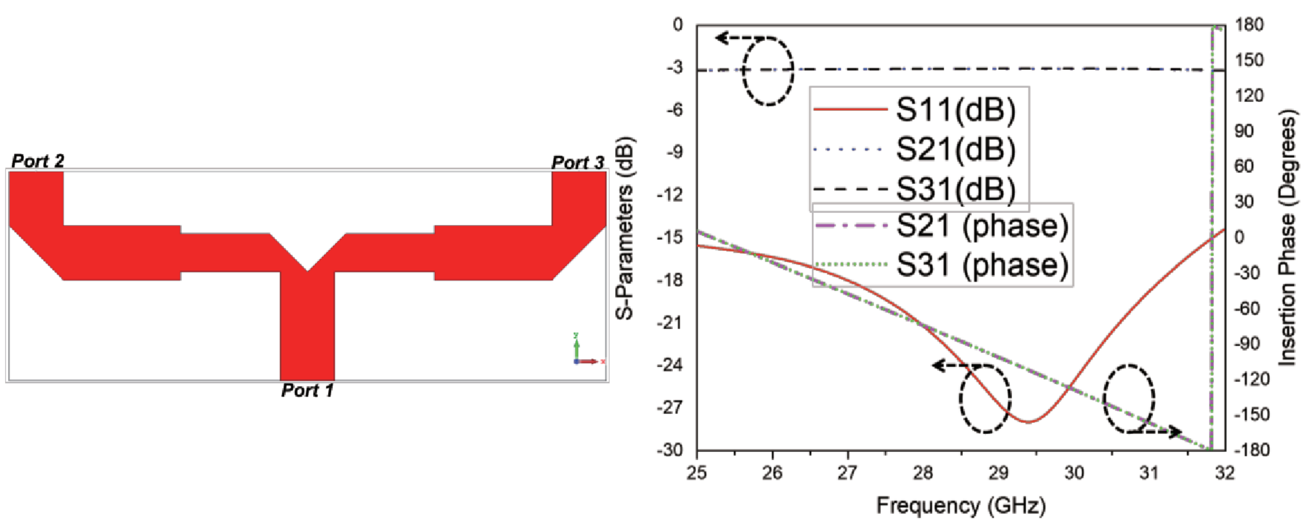


Figure 4. Realized gain and efficiencies of the antenna element.

3. PROPOSED 5G ANTENNA ARRAY

As the propagation of the 5G signals at mm-wave suffers from high path loss, a 16-element antenna array is formed based on the proposed antenna element in the previous section to improve the overall



(a) (b)

Figure 5. An example of the T-dividers in the feeding network (a) structure (b) S-parameters.

gain of the antenna. The spacing between any two adjacent elements is selected to be $0.5\lambda_0$ at the central frequency. The antenna elements are fed by a feeding network composed of 15 T-dividers. Each of these dividers has been initially designed separately matched at $50\,\Omega$ at its input/output terminals to split the power equally in magnitude and phase. Then, the 15 dividers have been merged to form a single 16-way equal power divider that works as the feeding network. As it would be very long to discuss the whole 15 dividers throughout the manuscript, an example of these dividers is shown in Figure 5 accompanied with its S-parameters.

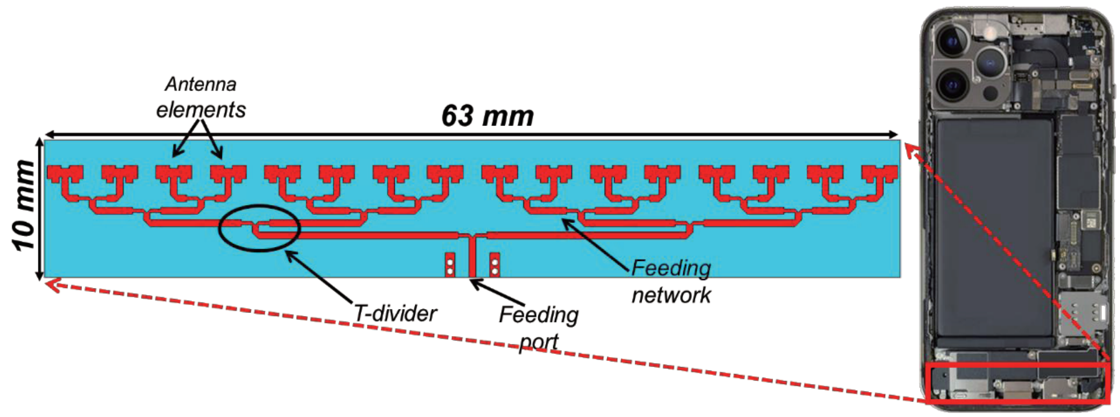


Figure 6. Structure of the proposed antenna array.

Figure 6 shows the structure of the proposed antenna array. The array overall size is $63 \times 10 \times 0.64\,\text{mm}^3$ which fits inside a smartphone chassis. To validate the idea, a prototype of the antenna array has been fabricated using printed circuit board (PCB) technology and measured as shown in Figure 7. The array is fed through a $50\,\Omega$ SMP connector. The proposed array has been designed and simulated using CST Microwave Studio, and the prototype has been measured using an Anritsu vector network analyser (VNA) and an anechoic chamber.

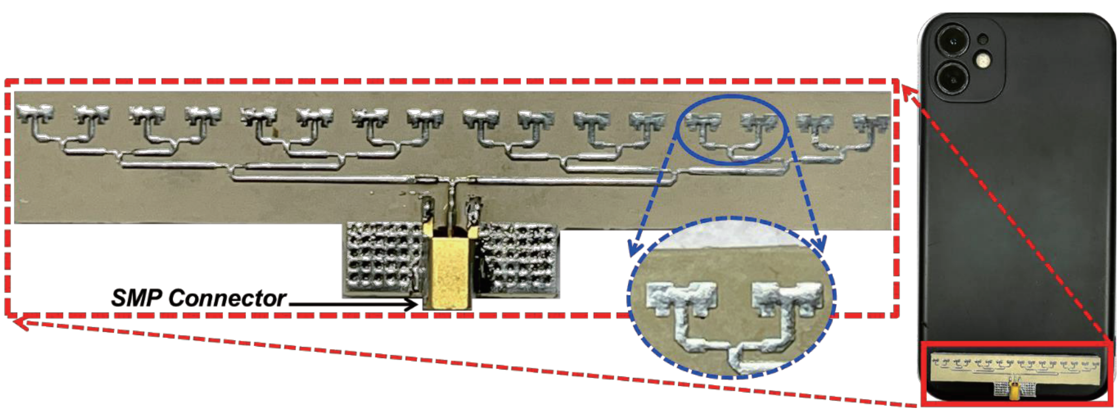


Figure 7. Prototype of the proposed antenna array.

Figure 8 shows the simulated and measured return losses and realized gains of the proposed antenna array. It is noticeable that there is a good agreement between simulated and measured results. The antenna array covers the frequency band from 25 to 32 GHz with a return loss of better than 10 dB (VSWR $\leq$ 2). The antenna realized gain is about 15 dBi across the frequency band.

The simulated and measured radiation patterns of the antenna array at the E-plane and H-plane are shown in Figures 9(a) and (b) respectively at 25 GHz, 29 GHz, and 32 GHz. The proposed antenna array has a wide HPBW of 110° at the E-plane and a narrow HPBW of 8° at the H-plane. The antenna

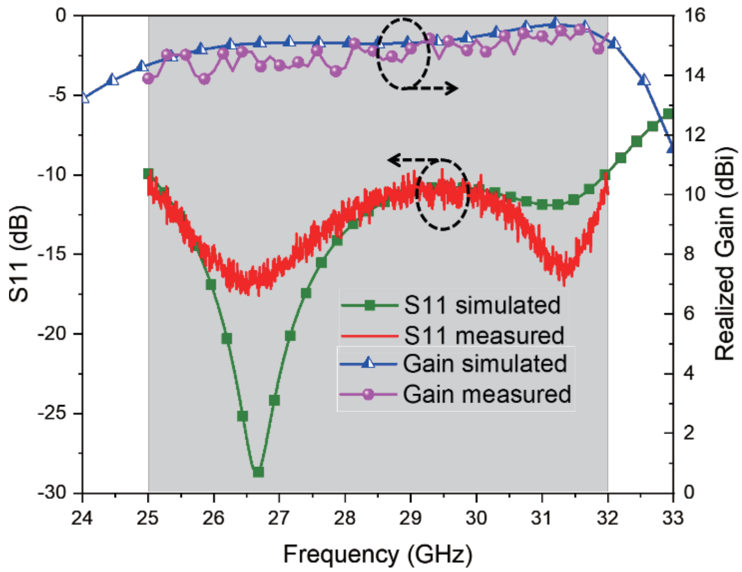


Figure 8. Return loss and realized gain of the proposed antenna array.

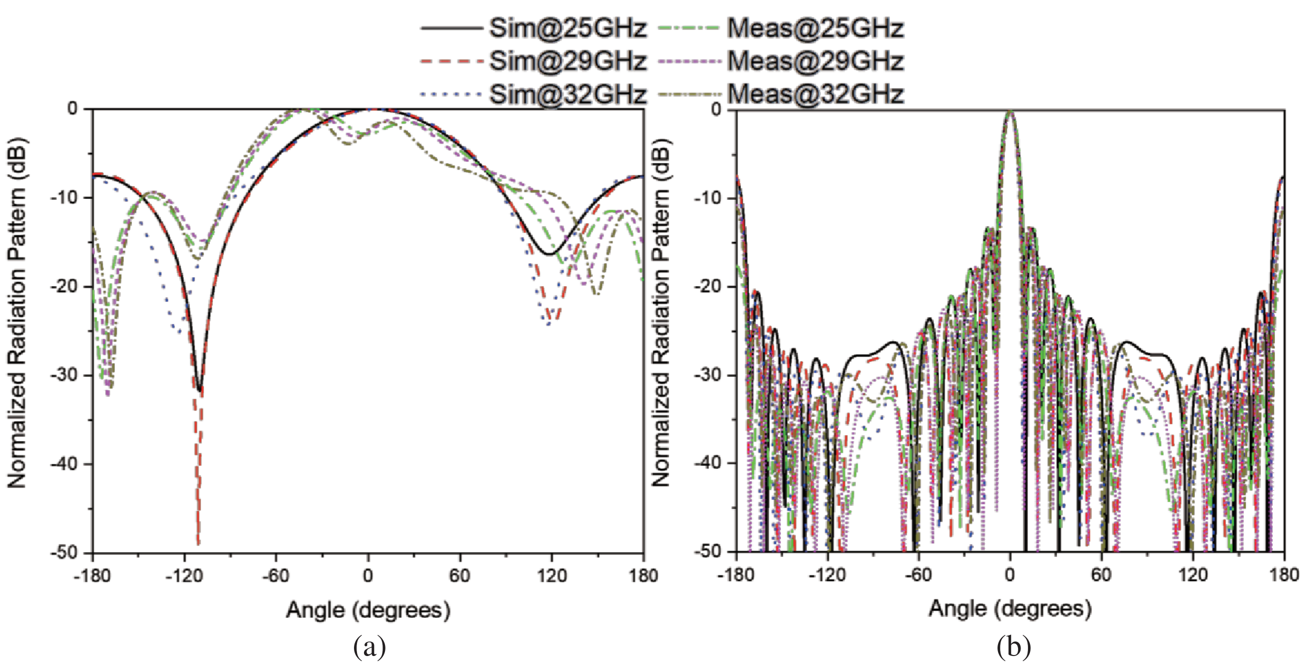


Figure 9. Simulated and measured radiation patterns of the proposed antenna array (a) E-plane (b) H-plane.

total efficiency has been calculated based on the measured realized gain and radiation HPBWs using antenna theories [12]. The total efficiency of the antenna array is $88 \pm 4\%$ across the frequency band.

4. BEAM STEERING OF THE ANTENNA ARRAY

Due to a narrow HPBW at the H-plane as discussed in the previous section, the spatial coverage of the radiation pattern in the XZ-plane is limited by 8°. Therefore, to improve the coverage, the electronic beam steering of the antenna array is utilized. In this section, a study is conducted, through simulations,

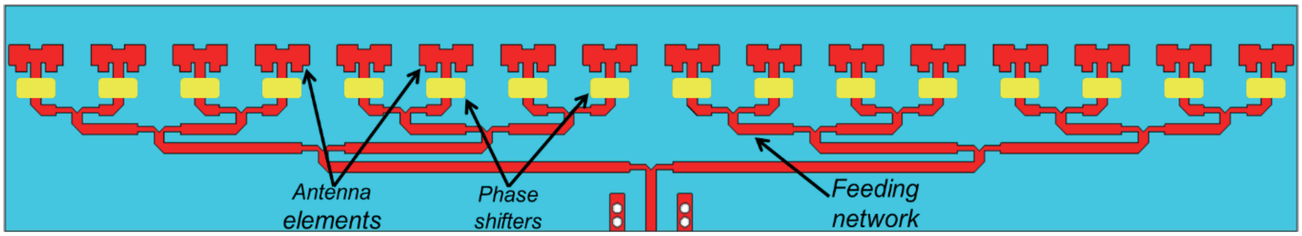


Figure 10. The proposed antenna array with digital phase shifters.

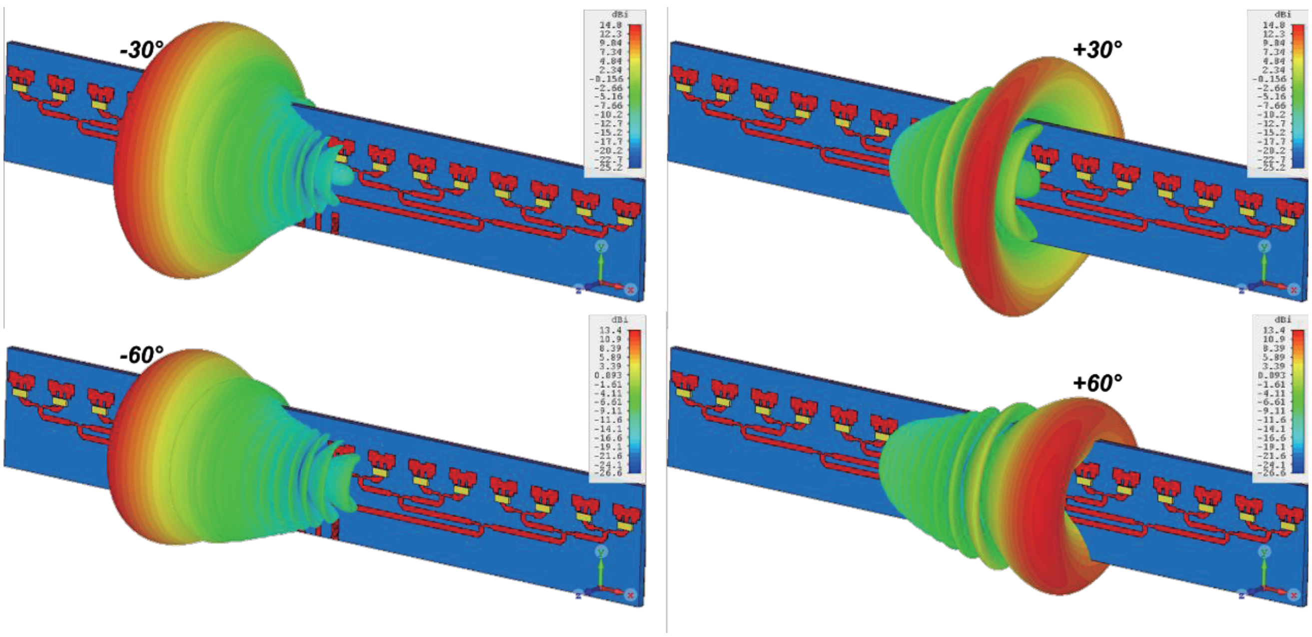


Figure 11. The radiation patterns of the proposed antenna array at different steering angles.

on the beam steering capabilities of the proposed antenna array.

The feeding network is connected to 16 digital phase shifters which are, subsequently, connected to the 16 antenna elements on a one-to-one basis as shown in Figure 10. The phase shifters are controlled digitally to provide the dedicated phase shift. Initially, when all the phase shifters are set to provide the same phase shift, the radiation pattern gives its maximum at boresight (Z-axis). By changing the phase progression of each phase shifter incrementally, the beam is steered in the XZ plane. Different steering angles are summarized in Figure 11 (angles towards $+X$ direction are denoted as positive angles while angles towards $-X$ direction are denoted as negative angles). The normalized radiation patterns across the H-plane at different steering angles are presented in Figure 12. It is evident that the antenna array has the ability to steer its beam within 120° (from +60° to −60°) with no significant degradation in its performance (less than a 2-dB drop in the antenna gain). Examples of the main beam steering angle and the corresponding phase shift at each phase shifter are summarised in Table 1.

To justify the performance of the proposed mm-wave antenna, a comparison to the state-of-the-art reported 5G antenna designs is tabulated in Table 2. The comparison is set in terms of the FBW, antenna size, antenna gain, and the simplicity of antenna structure.

It is evident that the proposed antenna has the broadest bandwidth. It is also the optimal design as it has a relatively small size and a high gain with a simple single-substrate structure and a low profile. The proposed antenna array is certainly a strong candidate for future 5G smartphone applications.

Table 1. Main beam direction and corresponding phase shifts.

Main beam direction (°)	Phase shifter (°)															
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+30	0	72	144	216	288	0	72	144	216	288	0	72	144	216	288	0
+60	0	125	250	15	140	265	30	155	280	45	170	295	60	185	310	75
−30	0	288	216	144	72	0	288	216	144	72	0	288	216	144	72	0

Table 2. Comparison to the state-of-the-art designs.

Design	Frequency band (GHz)	FBW (%)	Size (mm^3)	Gain (dBi)	Structure
[3]	27.4–28.4	3.6	$4 \times 0.2 \times 1.6$	10.2	Complex Multi-layer
[4]	27–29	7.1	$5.4 \times 0.6 \times 0.8$	11	Complex Multi-layer
[5]	26–30	14.3	–	–	Complex SIW layer
[6]	21–22	4.6	$4.3 \times 2 \times 0.8$	13.5	Simple Single-layer
[7]	28–32	13.3	$4.5 \times 0.2 \times 0.5$	12	Complex SIW layer
[8]	24–28	15.4	$3.25 \times 3.7 \times 0.8$	16.5	Simple Single-layer
[10]	26–31	17.5	$19.6 \times 11 \times 3$	15	Complex Multi-layer
[13]	26–32	20.7	$5.7 \times 2.8 \times 0.8$	13	Simple Single-layer
[14]	24–28	15.4	3.7 3.25.8	27	Simple Single-layer
[15]	28–33	16.4	——	6	Complex Multi-layer
[16]	24–28	15.4	3.2 3.2 0.8	15.5	Simple Single-layer
	24–30	22.2	6.2 4.15 0.8	15.1	Simple Single-layer
Proposed	**25–32**	**24.5**	$4 \times 2.8 \times 0.6$	**15**	**Simple Single-layer**

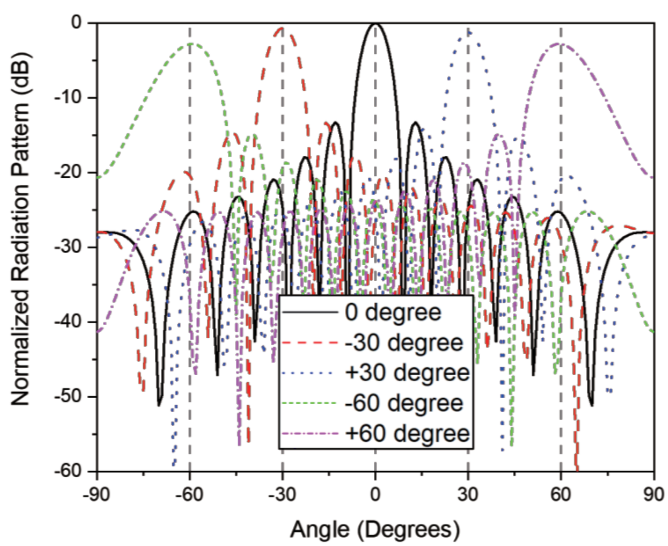


Figure 12. The normalized radiation patterns of the proposed antenna array at H-plane at different steering angles.

5. CONCLUSIONS

This paper proposes a novel low-profile broadband mm-wave antenna array for 5G smartphone applications. The array is constructed based on a conventional corporate feed antenna element that offers broadband (FBW of 24.5%), a stable radiation pattern and a simple structure in a low-profile single substrate. The antenna array has been simulated, fabricated, and measured. The array enjoys a high gain with a compact size that feasibly fits inside a smartphone chassis. The antenna array has been compared to several recent reported designs. The comparison shows that the proposed antenna offers the broadest BW and suitable performance to meet the requirements of the new 5G wireless communication systems. The array has been amended through simulations to perform an electronic beam steering to cover a wide spatial angle of 120°. The proposed antenna array has been proved to be an excellent candidate for 5G smartphone applications.

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