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Broadband Surface-Mount Differential-Fed Dipole Antenna and Its Array for 5G Millimeter-Wave Applications

Xiubo Liu[1], Wei Zhang[1], Dongning Hao[1], and Yanyan Liu[2, *]

Abstract—This letter proposes a differentially-fed broadband dipole and its 1×8 array. The antenna achieves cost-effectiveness by using a low-cost FR4 substrate. The antenna obtains surface mount capability due to the ball grid array (BGA) package. The measured results show that the proposed antenna array achieves a wide impedance bandwidth of 37.8% (24–35.2 GHz). The gain of the 1×8 array is greater than 10.1 dBi, and the cross-polarization level in the main beam direction is less than −20 dB. The radiation pattern of the 1×8 array is stable and unidirectional. The proposed antenna array covers the 5G N257 (26.5–29.5 GHz), N258 (24.25–27.5 GHz), and N261 (27.5–28.35 GHz) bands.

1. INTRODUCTION

The 5G millimeter-wave communication system can provide massive bandwidth and a high data rate to meet the ever-increasing demand for mobile data [1, 2]. Antennas play an important role in 5G wireless systems. Therefore, there is a great demand for broadband antennas with low cost and high integration characteristics.

Previous works usually used waveguide connectors [3, 4] or coaxial cables [5, 6] to interconnect with RF chipsets. However, antennas based on waveguide connectors or coaxial cables are bulky and difficult to integrate into wireless systems. To solve this issue, the Antenna-in-Package (AiP) [7, 8] was introduced, which integrates the antenna and RF chipset in the same package. Benefiting from advanced packaging technology [9], surface-mount antennas can be easily integrated into the system package without any bulky connectors. Numerous studies have been carried out to improve the integration of antennas [10–12]. On the other hand, the differentially-fed antenna can obtain wide bandwidths, good radiation patterns, and low cross-polarization [13, 14]. Our previous works [10, 12] introduced a single-ended antenna based on a BGA package, which achieves relatively low cost, medium antenna gain, and stable radiation pattern.

In this letter, to overcome the above-mentioned challenges, we propose a differentially-fed dipole antenna based on BGA packaging technology. A single FR4 substrate was introduced to achieve ultra-low-cost. In addition, the BGA packaging is investigated to facilitate integration. To further improve the antenna gain, a 1×8 array based on antenna elements is also proposed. The antenna design is described in detail in the following sections, and the prototype of the design is carefully verified. All simulation results are based on Ansys HFSS.

2. ANTENNA DESIGN

As depicted in Figure 1, the proposed antenna is designed using standard printed circuit board (PCB) processing on an FR4 substrate. The structure is simple and compact. To obtain a low cost, the

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* Corresponding author: Yanyan Liu (lyytianjin@nankai.edu.cn).
[1] School of Microelectronics, Tianjin University, Tianjin 300072, China. [2] Tianjin Key Laboratory of Photo-electronic Thin Film Devices and Technology, Nankai University, Tianjin 300071, China.

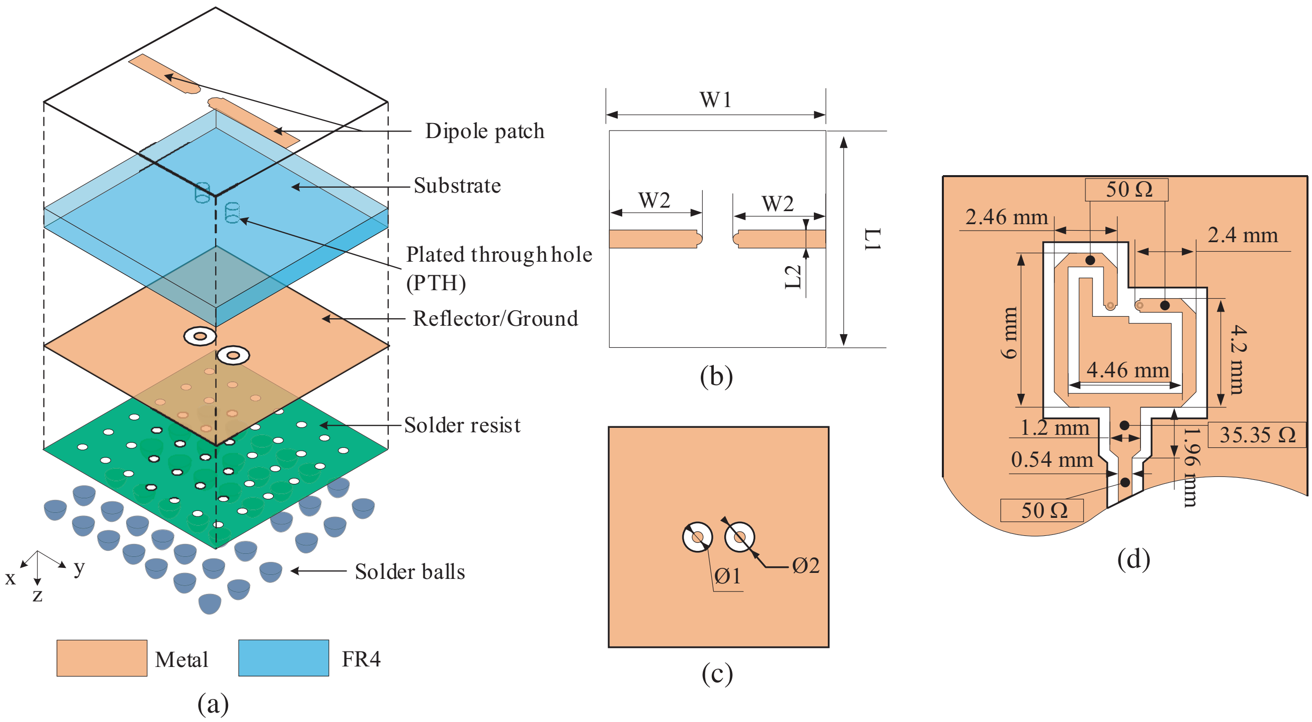


Figure 1. Geometry of the proposed antenna element. (a) Explored view. (b) Top view. (c) Bottom view. (d) Evaluation board.

antenna consists of only one dielectric layer with a thickness of 1.4 mm, a dielectric constant of 4.4, and a dielectric loss tangent of 0.02. Two symmetrical dipole patches are located on the top layer, while the metal ground is on the bottom layer.

Two plated through holes (PTH) are used to connect the dipole patch to the bottom-feed point. Furthermore, the solder resist layer is applied on the bottom layer for reflow soldering of solder balls. Finally, the solder balls are mounted on the bottom layer to form a BGA package. The input impedance of the differential port is set to 50 Ω to facilitate integration with the differential chipsets. After optimization in Ansys HFSS, the detailed dimensions of the antenna element are shown in Table 1. As shown in Figure 1(d), the evaluation board is used to evaluate the performance of the antenna. It is manufactured on a Rogers 4350B with a dielectric constant of 4.4, a dielectric loss tangent of 0.004, and a thickness of 0.254 mm. The T-junction power divider and 180-degrees delay line were made on the evaluation board to provide a pair of differential signals with the same amplitude and differential phase to the antenna elements.

Table 1. Dimensions of the proposed antenna element (Units: mm).

Parameters	Values	Parameters	Values
$L1$	6	$W1$	6
$L2$	0.5	$W2$	2.575
$\Phi1$	0.3	$\Phi2$	0.8

Figure 2 shows the E-field distribution of the antenna element at 28 GHz. It can be clearly observed that the RF signal flows from the solder ball through the PTH and is fed to the dipole patch on the top layer. Figures 3(a) and (b) illustrate the simulated gain, efficiency, and reflection coefficient of the antenna element. It can be seen that the -10 dB impedance bandwidth is 38.5% (24.3–35.9 GHz). The simulated gain is higher than 4.87 dBi, and the efficiency exceeds 83.35%.

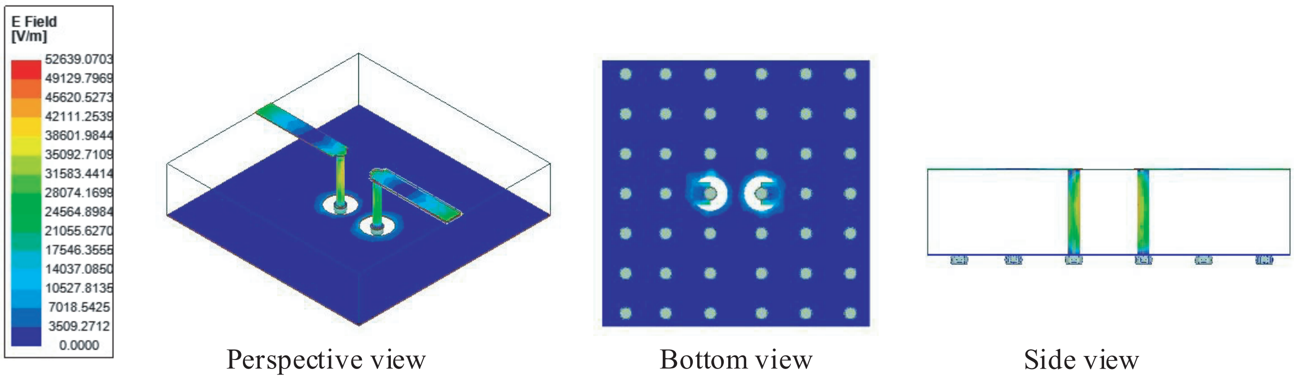


Figure 2. E-field distribution of the antenna element at 28 GHz.

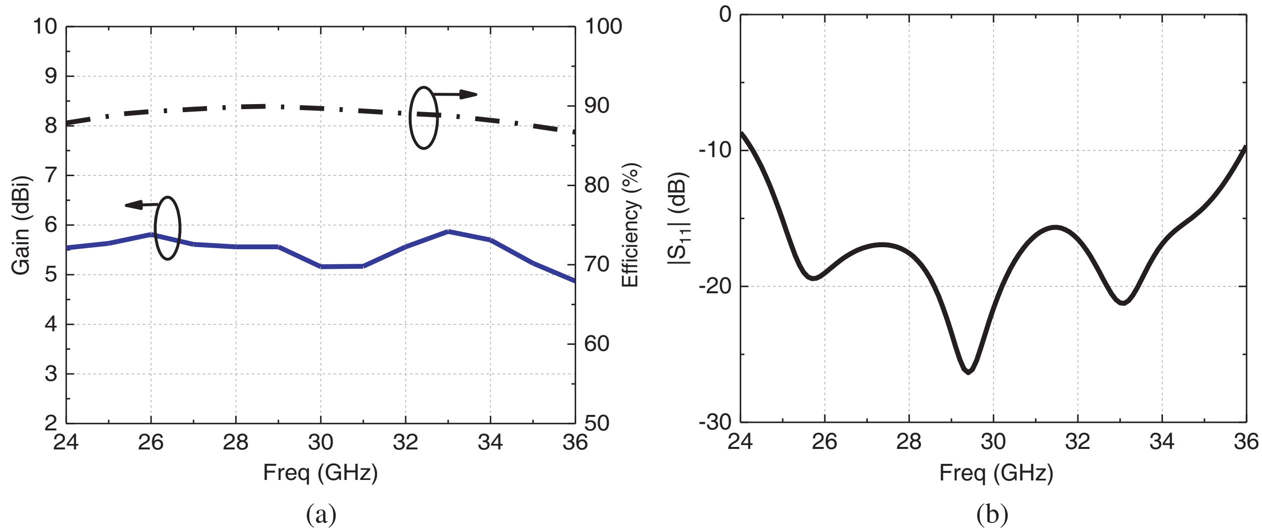
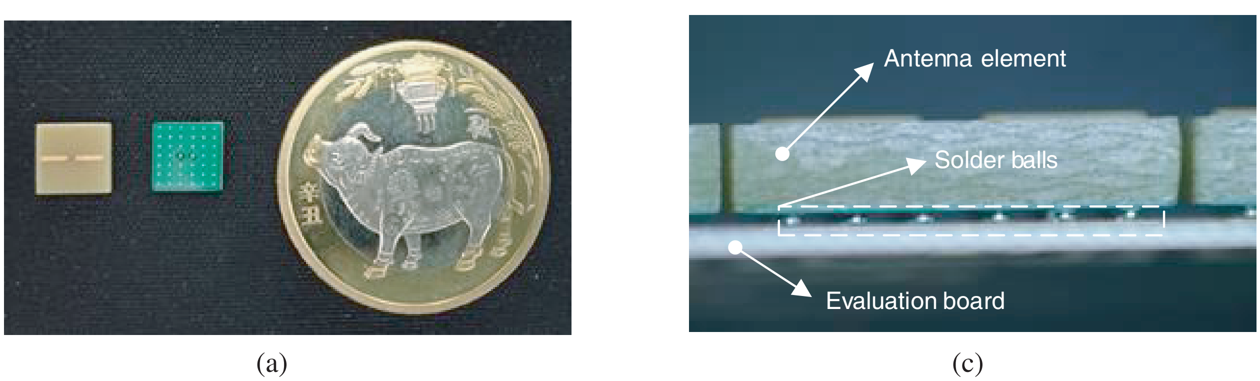


Figure 3. (a) Simulated gain and efficiency of the proposed element. (b) Simulated reflection coefficient of the proposed element.

3. MEASUREMENT RESULTS AND DISCUSSION

As shown in Figure 4, the antenna element and its array were fabricated for verification. The size of the antenna element is only $6\,\text{mm} \times 6\,\text{mm} \times 1.6\,\text{mm}$. In addition, it can be very flexibly extended to the array to obtain the desired gain and radiation pattern. As depicted in Figure 4(b), we extend the antenna



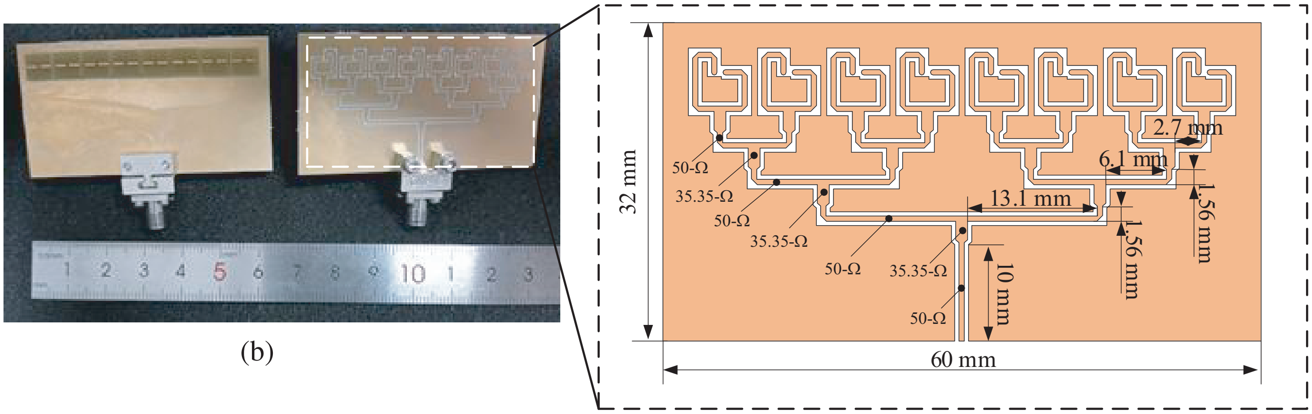
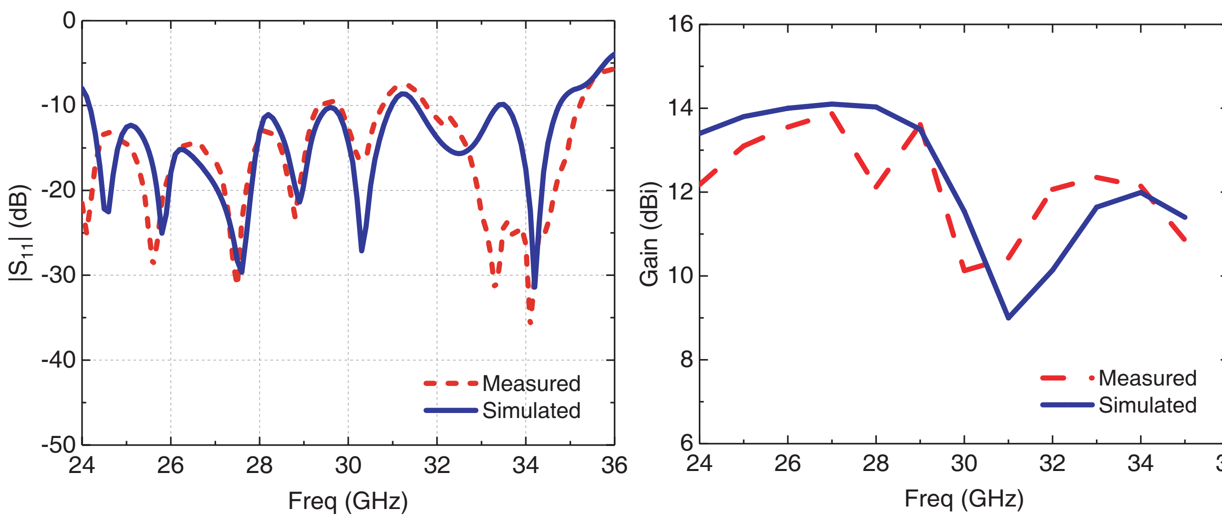


Figure 4. Photograph of the proposed prototype. (a) Single element. (b) 1×8 array. (c) Cross-section of the array.

element to a 1×8 array. As mentioned in Section 2, the evaluation board is also manufactured on the Ro4350B substrate with a size of 60 mm × 32 mm × 0.254 mm for measuring the antenna prototype. The T-junction power divider divides the RF signal into eight RF signals with the same amplitude and phase. The 180-degree delay line is then used to convert the single-ended signals into eight pairs of differential signals that are fed to the antenna element. The cross-section of the array is shown in Figure 4(c). The antenna elements are surface mounted on the evaluation board after reflow soldering. The 2.92 mm end launch connector (DC-40 GHz) is used to connect the evaluation board to the instrument. Finally, the network analyzer (Rohde & Schwarz, ZVA40) is used to measure the S-parameters, and the radiation patterns are measured in a standard far-field anechoic chamber.

Figure 5(a) shows the measured and simulated reflection coefficients $|S_{11}|$ of the 1×8 array. The measured and simulated impedance bandwidths are 37.8% from 24 to 35.2 GHz and 35.7% from 24.2 to 34.7 GHz, respectively. It can be noted that the simulation and measurement results are slightly higher than -10 dB at 29.7 and 31.5 GHz. It can also be seen that the impedance bandwidth covers the N257, N258, and N261 millimeter-wave bands of 5G. Figure 5(b) shows the measured and simulated antenna gains. The measured gain is 10.12 to 13.5 dBi, which is very close to the simulated ones. Figure 6



(a) (b)

Figure 5. (a) Measured and simulated $|S_{11}|$ of the prototype. (b) Measured and simulated gain of the prototype.

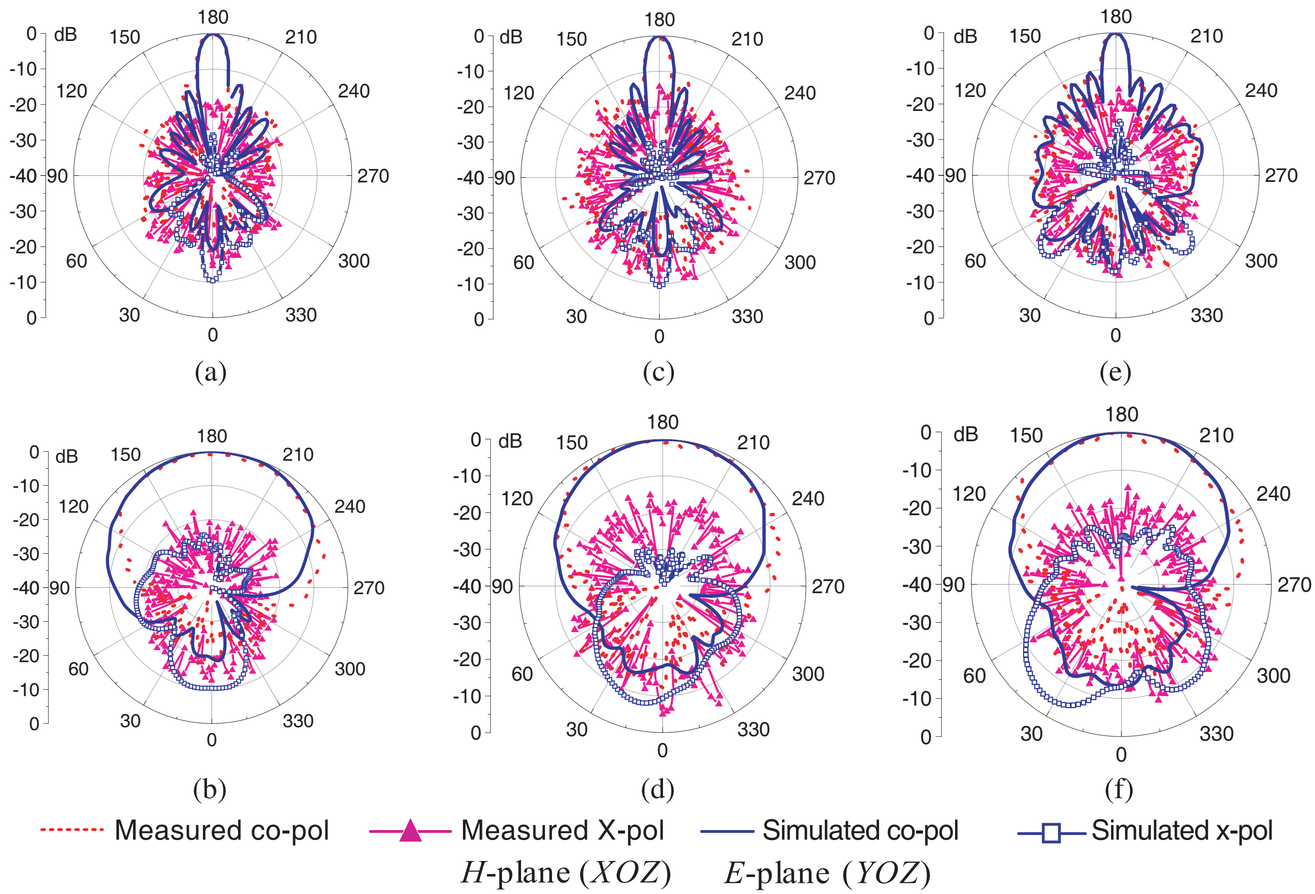


Figure 6. Measured and simulated normalization radiation patterns of the antenna element and array. (a) $f = 26$ GHz, E-plane. (b) $f = 26$ GHz, H-plane. (c) $f = 28$ GHz, E-plane. (d) $f = 28$ GHz, H-plane. (e) $f = 30$ GHz, E-plane. (f) $f = 30$ GHz, H-plane.

Table 2. Comparisons between the proposed and reported antenna.

Ref.	Antenna Type	F_0 (GHz)	Fractional bandwidth	Max. gain (dBi)	Dimension (λ_0^3)	Material
[3]	ME-dipole	30.15	18.9	16.6 (1×18 array)	$8.5 \times 1.39 \times 0.16$ (1×18 array)	RT 5880
[4]	Patches	27.9	8.6	7.41 (element)	$2.79 \times 1.85 \times 0.07$ (element)	TLY-5
[5]	Huygens source	27.915	2.14	4.54 (element)	$0.22 \times 0.19 \times 0.11$ (element)	RO5880
[10]	Dipole	30.55	35.7%	6.72 (element)	$0.61 \times 0.61 \times 0.16$ (element)	FR4
[11]	Yagi-Uda	26.87	19.53%	9.51 (1×4 array)	$1.88 \times 0.87 \times 0.013$ (1×4 array)	Glass
[12]	PIFA	27.15	15.3%	5.85 (element)	$4.5 \times 4.5 \times 1.3$ (element)	FR4
This work	Dipole	29.6	37.8%	13.8 (1×8 array)	$0.59 \times 0.59 \times 0.16$ (element)	FR4

shows the measured and simulated normalized radiation patterns of the array at 26, 28, and 30 GHz, respectively. Additionally, in the E-plane (YOZ), the cross-polarizations level of the element is less than −21, −21.8, and −21.6 dB in the main beam direction. In the H-plane (XOZ), the cross-polarizations level of the array is less than −33, −22, and −20 dB in the main beam direction. In general, it can be noticed that the measurement results are in good agreement with the simulation ones. Some slight discrepancies are caused by manufacturing tolerances.

Table 2 summarizes the performance comparisons between the proposed antenna and previous works. The parameters mainly include fractional bandwidth, maximum gain, dimension, and materials. It can be seen that the advantages of the proposed antenna are broadband bandwidth, low cost, compact size, and easy integration.

4. CONCLUSIONS

In this letter, a differentially-fed dipole and its 1×8 array have been demonstrated. The prototype has been simulated, manufactured, and verified. The proposed antenna array can achieve a wide impedance bandwidth of 37.8% (24–35.2 GHz), covering the 5G N257 (26.5–29.5 GHz), N258 (24.25–27.5 GHz), and N261 (27.5–28.35 GHz) bands. The compact size and easy integration make the proposed antenna very attractive for 5G millimeter-wave wireless systems.

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