

# Surface Mounted Microstrip Antenna Using Ball Grid Array Packaging for mmWave Systems Integration

Xi Wang<sup>1</sup>, Xiubo Liu<sup>1</sup>, Wei Zhang<sup>1</sup>, Dongning Hao<sup>1</sup>, and Yanyan Liu<sup>2, \*</sup>

**Abstract**—In this letter, two cost-effective surface-mount patch antenna elements for millimeter-wave (mmWave) systems using ball grid array (BGA) packaging are presented. A single-layer substrate based on FR4 is used to meet the low-cost requirements. The BGA packaging makes the proposed antenna element compact and easy to integrate. A U-slot is added to the patch to improve the impedance bandwidth of the patch antenna, and a vertical transition is designed to transmit the excitation signal by using a plated through-hole (PTH). The design process of the antenna is illustrated in detail. The antenna prototype has been simulated, fabricated, and measured to validate the design. The size of the fabricated prototype is  $5\text{ mm} \times 5\text{ mm} \times 1.3\text{ mm}$ , which is very suitable for integration into a mmWave system.

## 1. INTRODUCTION

Microstrip antennas are the most widely used antennas in wireless systems because of their advantages such as low cost, small size, and convenient manufacture [1–3]. To increase the bandwidth, a U-slot is added to improve the bandwidth of the patch antenna [4–7]. However, the main disadvantage of the above-mentioned patch antenna is the use of high-loss coaxial cables for interconnection. On the one hand, the coaxial cable increases the insertion loss between the antenna and RF amplifier. On the other hand, the large size is difficult to integrate into the system.

Antenna-in-package (AiP) is a highly integrated solution that can achieve the low-loss interconnection between the antennas and RF chipsets [8–10]. In addition, flip-chip interconnect can reduce insertion loss and improve RF system performance, instead of using bulky and lossy coaxial connectors [11] or waveguide connectors [12].

In this letter, two small-size and low-cost BGA packaged patch antenna elements are proposed. Taking advantage of the advantages of the patch antenna and AiP technology, the compact BGA packaged antenna element is suitable for integration with other surface mount devices (SMDs) in the same package. The simulated results and experimental results are given and discussed. The antenna elements have been designed, fabricated, and measured. The antenna has a wide bandwidth and a stable radiation pattern. All simulation results are given by ANSYS electromagnetics.

## 2. ANTENNA GEOMETRY AND DESIGN

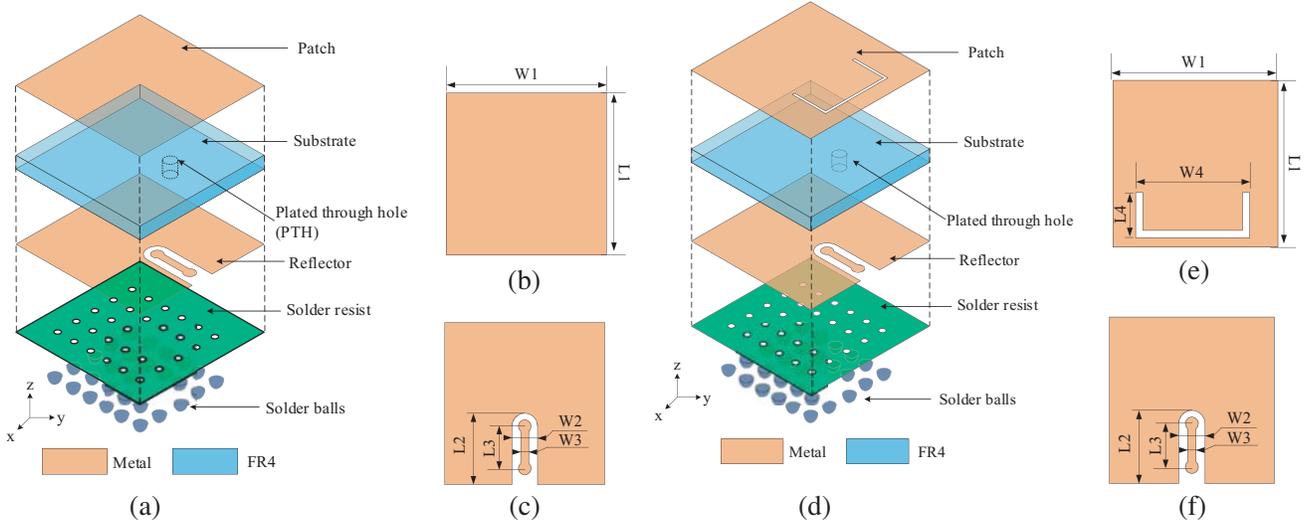
Figures 1(a), (b), and (c) show the geometry of the proposed patch antenna element without the U-slot (Ant 1). Figures 1(d), (e), and (f) show the geometry of the proposed patch antenna element with the U-slot (Ant 2). The dimensions of the antenna elements are the same, and Ant 2 adds a U-slot based on Ant 1. The antenna element is fabricated on a low-cost FR4 substrate with a dielectric constant

---

*Received 12 May 2021, Accepted 11 June 2021, Scheduled 22 June 2021*

\* Corresponding author: Yanyan Liu (lyytianjin@nankai.edu.cn).

<sup>1</sup> School of Microelectronics, Tianjin University, Tianjin 300072, China. <sup>2</sup> Tianjin Key Laboratory of Photo-electronic Thin Film Devices and Technology, Nankai University, Tianjin 300071, China.



**Figure 1.** Geometry of the proposed antenna element. Ant 1: (a) Exploded view. (b) Top view. (c) Bottom view. Ant 2: (d) Exploded view. (e) Top view. (f) Bottom view.

of 4.25, dielectric loss tangent of 0.018, and thickness of 1.1 mm. Two conductive layers are realized on the top and bottom layers of the antenna element. To obtain a directional radiation pattern, the bottom metal acts as a reflective ground. The 0.2 mm plated through-hole (PTH) is a vertical transition that connects the patch and the feedline at the bottom layer. The length of the feedline is a quarter-wavelength and is used for impedance matching. The solder resists layer is coated on the bottom metal layer. Solder balls with a diameter of 300 microns are mounted on the bottom layer of the element. In addition, to facilitate integration with the RF chipset, the input impedance of the patch element is set to  $50\ \Omega$ . After electromagnetic simulation, the dimensions are summarized in Table 1. The final size is  $5\ \text{mm} \times 5\ \text{mm} \times 1.3\ \text{mm}$ .

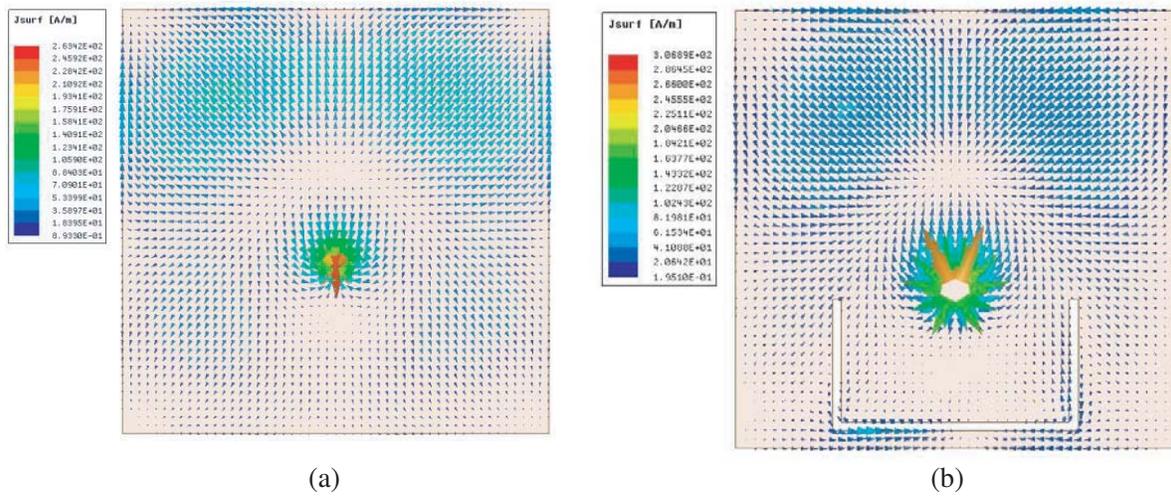
**Table 1.** Dimensions of the proposed antenna element (Units: mm).

Parameters	Values	Parameters	Values
$L1$	5	$W1$	5
$L2$	2.2	$W2$	0.8
$L3$	1.3	$W3$	0.2
$L4$	1.5	$W4$	2.8

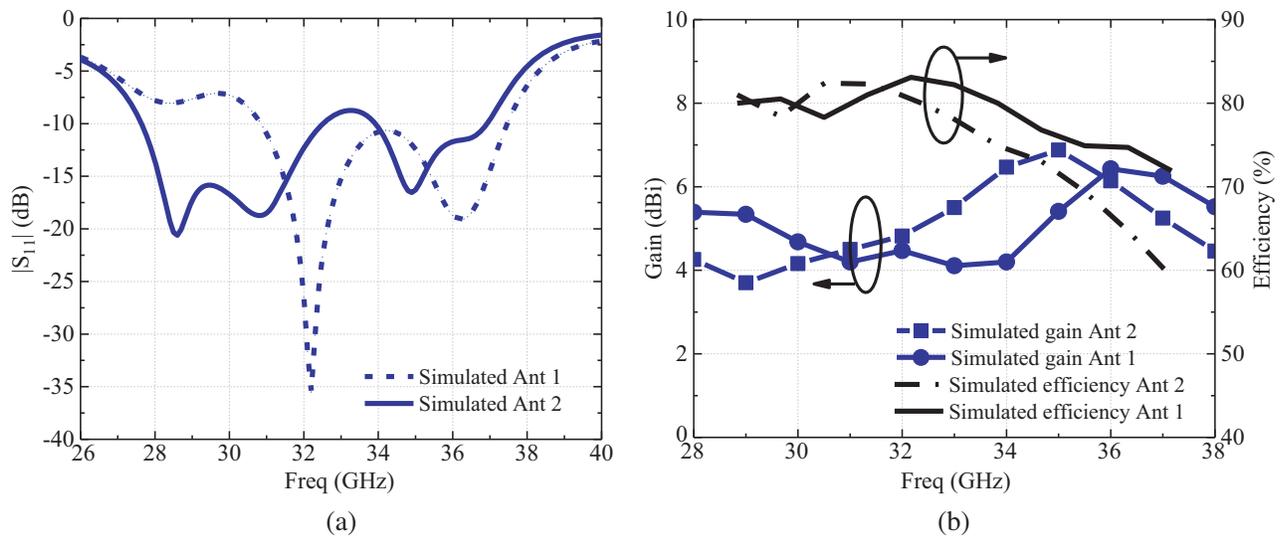
Figure 2 shows the surface current distribution of the antenna element at 32 GHz. It indicates that the patch is strongly excited by the PTH. The U-slot adds a path and enhances the current intensity. Figure 3 shows the performance of the prototype with and without the U-slot. It can be seen that the  $-10\ \text{dB}$  impedance bandwidth of Ant 1 ranges from 30.9 to 37.4 GHz. Due to the addition of U-slots, the bandwidth of Ant 2 is wider than that of Ant 1. The  $-10\ \text{dB}$  impedance bandwidths of Ant 2 are 27.7 to 32.5 GHz and 34 to 36.9 GHz. In addition, Ant 1 has a gain range of 4.11 to 6.43 dBi, and Ant 2 has a gain range of 3.7 to 6.88 dBi. In the range of 28 to 38 GHz, the simulation efficiencies of Ant 1 and Ant 2 reach more than 71.9% and 59.2%, respectively.

### 3. MEASUREMENT RESULTS AND DISCUSSION

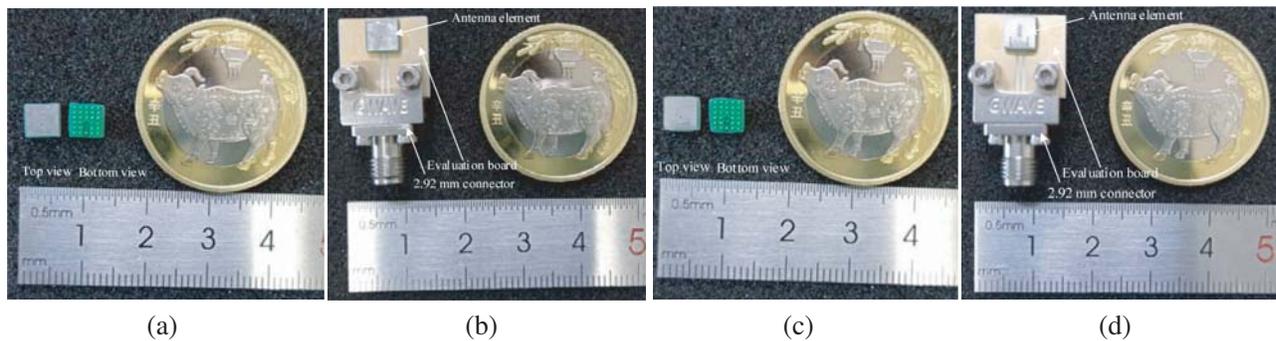
To verify the proposed design, the prototype was fabricated using the low-cost printed circuit board (PCB) technique, as shown in Figure 4. An evaluation board with a  $50\ \Omega$  coplanar waveguide (CPW) transmission line was used to measure the proposed antenna element. Furthermore, the proposed



**Figure 2.** Surface current distribution of the proposed antenna element at 32 GHz. (a) Ant 1. (b) Ant 2.



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

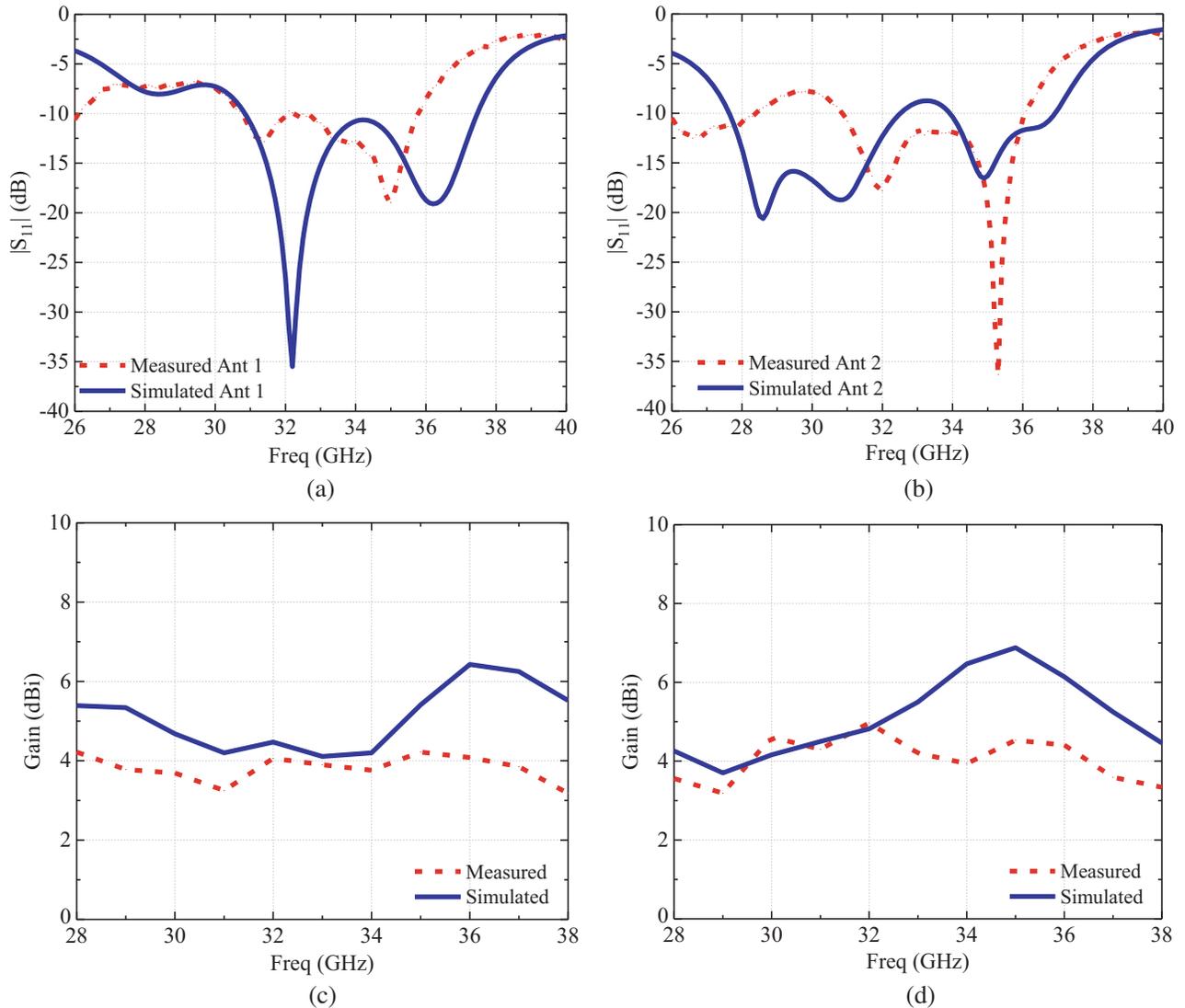


**Figure 4.** Photograph of the patch antenna prototype. Ant 1: (a) Antenna element. (b) Assembly prototype. Ant 2: (c) Antenna element. (d) Assembly prototype.

antenna element is surface-mount on the top layer of the evaluation board after reflow-soldering. In addition, a 2.92 mm end launch connector with operating frequencies from DC to 40 GHz was installed at the edge of the evaluation board. The reflection coefficient is measured by Rohde & Schwarz Network Analyzer (ZVA40). The far-field radiation patterns are measured in an anechoic chamber.

Figures 5(a) and (c) show the simulated and measured reflection coefficients and gains of Ant 1, respectively. The measured impedance bandwidth of  $-9.72$  dB is in the range of 30.8 to 35.7 GHz, which is slightly narrower than the simulated bandwidth. In the range of 28 to 38 GHz, the measured peak gain is 3.18 to 4.22 dBi. Figures 5(b) and (d) show the simulated and measured reflection coefficients and gains of Ant 2, respectively. The measured impedance bandwidth of  $-10$  dB ranges from 30.9 to 36 GHz. The measured gain ranges from 3.19 to 4.97 dBi. Figure 6 shows the simulated and measured  $E$ -plane and  $H$ -plane normalized radiation patterns at 32 GHz, 34 GHz, and 36 GHz, respectively.

It can be seen that there are discrepancies between the simulated and measured results. As mentioned in [1], the tolerance control has a great influence on the performance of the microstrip antenna in the millimeter frequencies. Through the analysis of the parameters, we find that the difference is



**Figure 5.** (a) Measured and simulated reflection coefficient of the Ant 1. (b) Measured and simulated reflection coefficient of the Ant 2. (c) Measured and simulated peak gain of the Ant 1. (d) Measured and simulated peak gain of the Ant 2.

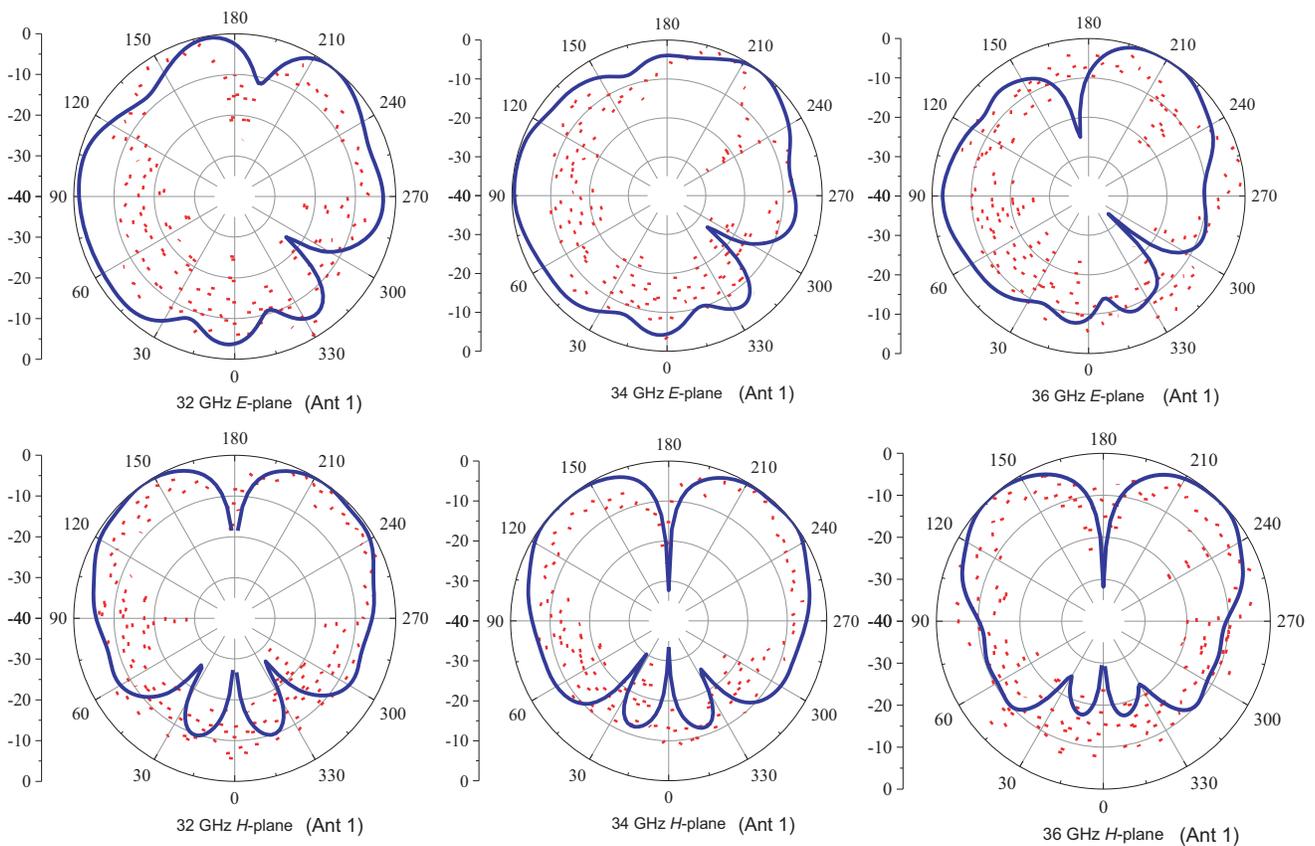
**Table 2.** Comparisons between the proposed and reported antennas.

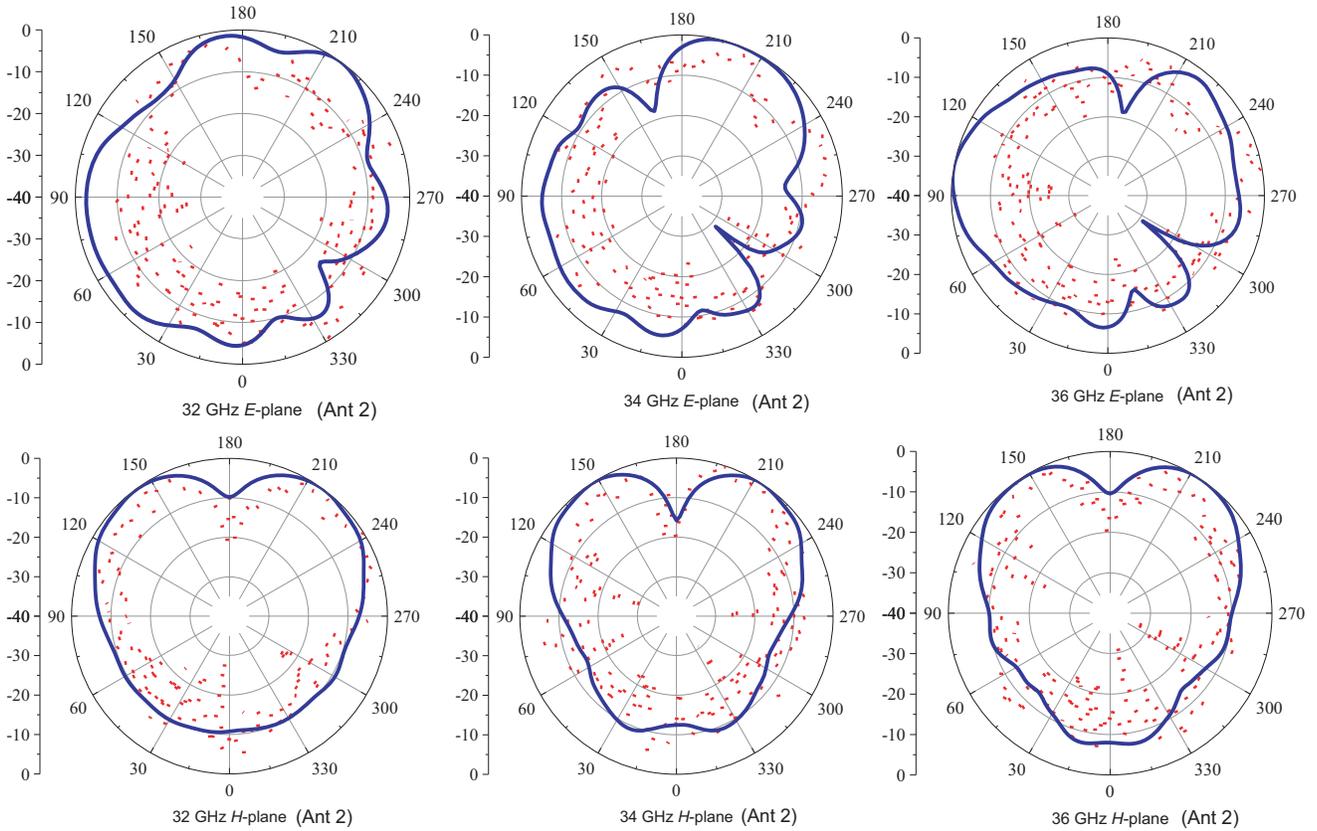
Ref.	Antenna type	Fc	Imp. BW (-10 dB) (%)	Measured peak gain (dBi)	Dimensions (mm <sup>3</sup> )	Material	Interconnection
[11]	Huygens source	27.91	2.14	4.54	2.4 × 2 × 1.143	Rogers5880	Coaxial line
[12]	Patch	27.9	8.6	7.41	19.9 × 30 × 0.79	TLY-5	Waveguide
This work	Patch (Ant 1)	33.35	14.7 *	4.22	5 × 5 × 1.3	FR4	Surface-mount
	Patch (Ant 2)	33.45	15.2	4.97	5 × 5 × 1.3	FR4	Surface-mount

\* -9.72 dB

mainly caused by the fabrication error, such as the thickness of the substrate and the position of the PTH. The radiation pattern of the *E*-plane is slightly tilted due to the 2.92 mm connector.

Table 2 summarizes the performance comparison between the recommended antenna and the reported antenna. It can be seen that the antennas in [11] and [12] have to use bulky and lossy waveguide connectors or coaxial cables to interconnect with the RF chipset. Meanwhile, the proposed antenna is a BGA packaged element that can be surface-mounted with other active devices or integrated into the system without using connectors. Low-cost FR4 substrate is also an attractive material to meet cost-effectiveness requirements.





**Figure 6.** Simulated and Measured  $E$ -plane and  $H$ -plane normalized radiation patterns at 26 GHz, 28 GHz and 30 GHz.

#### 4. CONCLUSIONS

A surface-mount microstrip antenna based on the BGA packaging has been proposed. The prototype has been simulated, fabricated, and measured. Based on the BGA packaging, the antenna element achieves a compact size and surface-mount function. Cost-effective functions can be obtained by using a single-layer low-cost FR4 printed circuit board. In addition, the performance of the patch antenna will be sensitively affected by mechanical manufacturing errors. Therefore, to obtain good performance, manufacturing tolerances should be strictly limited. The proposed antenna is a good choice for integration into millimeter-wave systems.

#### ACKNOWLEDGMENT

This work was supported by the Tianjin Research Innovation Project for Postgraduate Students under Grant 2020YJSB008.

#### REFERENCES

1. Carver, K. and J. Mink, "Microstrip antenna technology," *IEEE Trans. Antennas Propag.*, Vol. 29, No. 1, 2–24, Jan. 1981.
2. Garcia Zuazola, I. J., A. Sharma, M. Filip, and W. G. Whittow, "Antenna using a magnetic-slab located in the principal magnetic-field region beneath the patch," *Progress In Electromagnetics Research C*, Vol. 110, 229–241, 2021.

3. Kaur, K., A. Kumar, and N. Sharma, "Split ring slot loaded compact CPW-fed printed monopole antennas for ultra-wideband applications with band notch characteristics," *Progress In Electromagnetics Research C*, Vol. 110, 39–54, 2021.
4. Khan, M. and D. Chatterjee, "Analysis of reactive loading in a U-slot microstrip patch using the theory of characteristic modes [Antenna applications corner]," *IEEE Antennas Propag. Mag.*, Vol. 60, No. 6, 88–97, Dec. 2018.
5. Liu, S., S.-S. Qi, W. Wu, and D.-G. Fang, "Single-layer single-patch four-band asymmetrical U-slot patch antenna," *IEEE Trans. Antennas Propag.*, Vol. 62, No. 9, 4895–4899, Sep. 2014.
6. Mok, W. C., S. H. Wong, K. M. Luk, and K. F. Lee, "Single-layer single-patch dual-band and triple-band patch antennas," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 8, 4341–4344, Aug. 2013.
7. Lee, K. F., S. L. Steven Yang, A. A. Kishk, and K. M. Luk, "The versatile U-slot patch antenna," *IEEE Antennas Propag. Mag.*, Vol. 52, No. 1, 71–88, Feb. 2010.
8. Zhang, Y. P. and D. Liu, "Antenna-on-chip and antenna-in-package solutions to highly integrated millimeter-wave devices for wireless communications," *IEEE Trans. Antennas Propag.*, Vol. 57, No. 10, 2830–2841, Oct. 2009.
9. Zhang, Y., "Antenna-in-package technology: Its early development [Historical corner]," *IEEE Antennas Propag. Mag.*, Vol. 61, No. 3, 111–118, Jun. 2019.
10. Zhang, Y. and J. Mao, "An overview of the development of antenna-in-package technology for highly integrated wireless devices," *Proc. IEEE*, Vol. 107, No. 11, 2265–2280, Nov. 2019.
11. Tang, M., T. Shi, and R. W. Ziolkowski, "A study of 28 GHz, planar, multilayered, electrically small, broadside radiating, huygens source antennas," *IEEE Trans. Antennas Propag.*, Vol. 65, No. 12, 6345–6354, Dec. 2017.
12. Park, J., J. Ko, H. Kwon, B. Kang, B. Park, and D. Kim, "A tilted combined beam antenna for 5G communications using a 28-GHz band," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 15, 1685–1688, 2016.