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High-order-mode cavity fed 45° linear polarized antenna for 5G applications

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Research Paper

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Abstract

In this paper, a high-order-mode (HOM) (TE_{330}) cavity-fed 45° linear polarized 6×6 slot array antenna is proposed. The 45° linear polarization is achieved by introducing asymmetric cross slots on the HOM cavity, resulting in low profile and wide bandwidth. The antenna array was verified using standard printed circuit board technology. Measured results show that the impedance bandwidth ($|S_{11}| \leq -10$ dB) is 13.9% (36.98–42.92 GHz), and the peak gain is 19.3 dBi with a 3-dB gain bandwidth of 13.6%. Attributed to its simple structure, low profile, and wide bandwidth, the presented antenna is a good candidate for 5G applications.

Introduction

Recently, millimeter-wave bands have been used to improve the overall system performance [1, 2, 6, 7]. For radar detection and the fifth generation mobile communications (5G), higher transmission quality can be achieved through improving anti-interference ability in certain specific situations. 45° linear polarized antennas facilitate advanced beamforming and beam steering techniques, allowing precise beam direction toward users, improving signal strength, and reducing interference, which have been extensively employed in practical communications [3, 4, 9, 23]. Moreover, they find applications in high-resolution radar systems for security and surveillance, providing detailed imagery and enhanced detection capabilities [5, 16].

Loading an additional layer between the feed network and the radiation part and increasing the thickness of the radiation slots are the main methods for achieving 45° linearly polarized hollow-waveguide-fed array antennas [3, 8, 9]. In [3], the hollow-waveguide-fed array antenna is proposed with a high cross-polarization discrimination (XPD) level of 31.5 dB. However, the antenna profile has a high thickness of 6.6 mm, which is 1.32 wavelengths at the center frequency of 60 GHz. Moreover, the impedance bandwidth of the hollow-waveguide antenna is only 6.5%. In [8], excessive etching occurs during the milling process of thin metal plates, when a radiation slot layer is loaded into a traditional planar stacked antenna. Due to the presence of weak parts that are prone to break and cumb in the hollow-waveguide antenna prototype, the measured impedance bandwidth is only 3.3% and the efficiency is 50%. On the basis of [3], [9] improves the antenna performance, achieving a bandwidth of 19.2%, an efficiency of 86.6%, and an XPD level of 30 dB in the E-band. However, the complexity of the antenna design may lead to more machining errors, thereby increasing the uncertainty of measured results.

Continuous transverse stub array antennas are used for high XPD level and efficient linearly polarized antennas [10–12]. In [12], the 45° linearly polarized antenna consists of four layers: the feed network, cavity layer, radiating slots on continuous transverse stub, and 45° linear polarizer, achieving a high XPD level of 41 dB while maintaining an aperture efficiency of over 74%. But compared to [10], the linear polarizer adds two additional layers, resulting in increased profile and processing complexity.

In order to solve the complex structural problems mentioned and improve the antenna performance, researchers have replaced the antennas containing a complex feed network with a substrate-integrated waveguide (SIW) antenna array. The conventional way to achieve a 45° linearly polarized antenna is to etch the 45° inclined slots on the top metal layer of the SIW [13–16]. In [13], the 45° linearly polarized antenna using SIW technology is achieved through two layers of standard printed circuit boards (PCBs), which, however, suffers a narrow bandwidth of only 2.88%. In [14], a series slot coupling antenna by alternating inductive and capacitive loading is proposed to achieve low profile and small size. Unfortunately, the narrow antenna bandwidth can only cover 2.7%, and the XPD level is 13.81 dB, which requires other technologies to optimize, such as dielectric resonator antenna and coaxial line [15, 16]. In recent years, higher-order-mode cavities have been introduced in millimeter-wave antennas [17–19], due to their advantages of high efficiency and compact size. In fact, above 45° linearly polarized antennas do not use higher-order mode cavities. In [19], a 45° linear polarized antenna is achieved

by TE_{170}-cavity-fed C-shaped patches with an efficiency of 98.9% and an XPD level of 20 dB. However, the impedance bandwidth is only 9.17%, which still needs to be improved.

This paper presents a method to achieve a 45° linear polarized 6×6 slot antenna array with high performance by means of asymmetric cross slots etched on the high-order-mode (HOM) cavity. The proposed antenna achieves broadband, high radiation efficiency, and high XDP level, while also having the advantages of simple structure and low profile. This paper is organized as follows. The 3×3 subarray design section describes the HOM cavity working principle and 3×3 subarray design. The 6×6 array design section presents the 6×6 antenna array, followed by the Conclusion section.

3×3 subarray design

The proposed 3×3 subarray is shown in Fig. 1. The subarray consists of one substrate layer and two metallic layers. The monolayer substrate is Rogers 5880 with a thickness of 1.575 mm. The asymmetric orthogonal slots with a length, width, and offset of 3 mm, 1.2 mm, and 0.25 mm are etched at the upper metal layer. The high-order mode TE_{330} in the square SIW cavity is excited by the coaxial feeding. The resonant frequency of the mode is given as follows:

$$f_{mnp} = \frac{c}{2\pi\sqrt{\mu\varepsilon}}\sqrt{(\frac{m\pi}{L_{eff}})^2 + (\frac{n\pi}{W_{eff}})^2 + (\frac{pm\pi}{h})^2}, \quad (1)$$

$$\begin{aligned} L_{eff} &= L - \frac{d^2}{0.95p}, \\ W_{eff} &= W - \frac{d^2}{0.95p}, \end{aligned} \quad (2)$$

where W, L, and h are the width, length, and height of the SIW cavity (SIWC) and d and p are the diameter and spacing of the SIW vias, respectively. The TE_{330} mode inside SIWC means $m = 3$, $n = 3$, and $p = 0$. The permeability and permittivityof the substrate μ and ε are 1 and 2.2, respectively. The electric field is determined by (3), where E_0 and ϕ are the amplitude and phase of the waves [20],

$$E_{Z,\,TE_{330}} = E_0 \sin\frac{3\pi x}{L_{eff}} \sin\frac{3\pi y}{W_{eff}} \cos(\omega t + \phi). \quad (3)$$

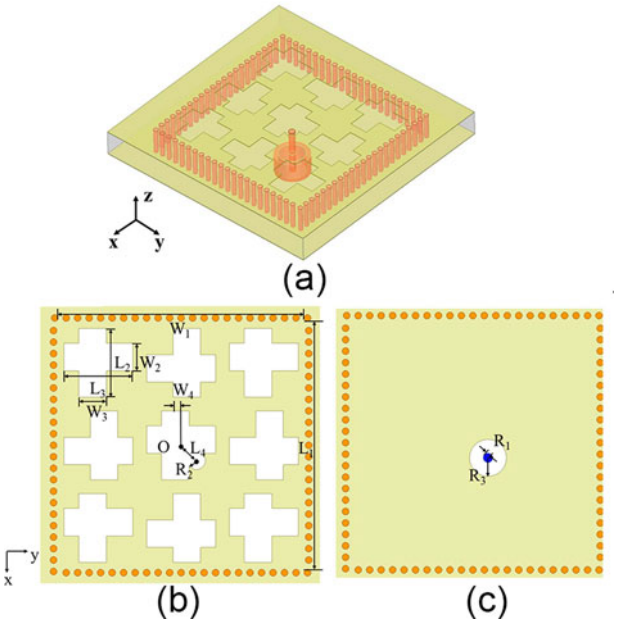

Figure 1. Subarray antenna: (a) over view, (b) top view, and (c) bottom view.

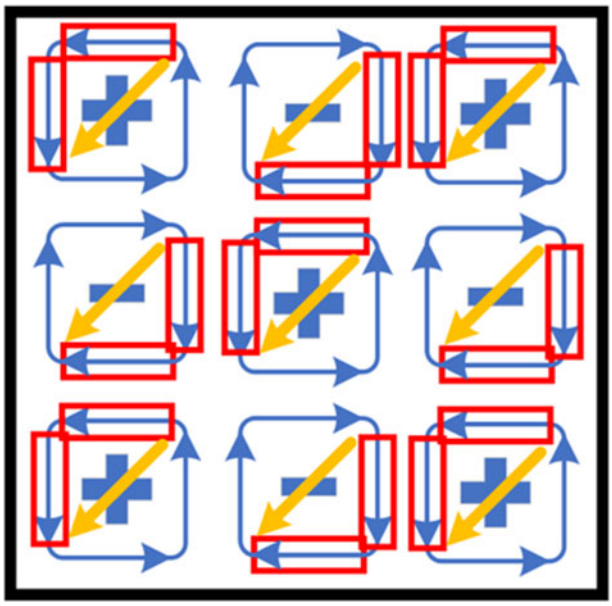

Figure 2. Electric field and magnetic vector of TE_{330} mode.

The 45° linear polarization is achieved by introducing asymmetric orthogonal slot radiation into the copper layer, which is on the top layer of the HOM cavity. To better explain the principle of the slot position by HOM cavity, the distribution diagram of electric and magnetic fields of the TE_{330} mode is shown in Fig. 2. The 3×3 standingwave electric peaks are evenly distributed inside the SIWC. The signs "+" and "−" represent the direction of the electric field. The closed curves indicate the magnetic vector, and its arrow direction is the vector direction. The offset transverse and the longitudinal slots with the same size are etched in each segment along the horizontal and vertical directions of the magnetic field vector. The electric field distributions at the radiation slots in this paper have the same phase. Due to the same size of the horizontal and vertical slots, the orthogonal components in the horizontal and vertical directions are of equal amplitude. A sum magnetic field vector can be formed, resulting in the radiation of 45 ° linearly polarized electromagnetic waves.

Note that the directions of the electric field in adjacent subsections are out of phase, and the directions of rotation of the magnetic field vector are opposite. Therefore, radiation in the same phase and same polarization requires etching a pair of orthogonal slots at positions with the same vector direction in each subsection. In the same way, −45° linear polarization can also be achieved in this way, and the diverse linear polarizations can be realized by designing this pair of the orthogonal slots into different size. Figure 3 illustrates the electric field distribution before and after etching the slots for the purpose of the effect of the asymmetric cross slots on the antenna radiation.

In order to achieve better antenna performance, it is necessary to determine the size of the cavity in the antenna and the mode excited within it. Figure 4 shows different antenna design and performance comparison using TE_{330} mode and TE_{340} mode.

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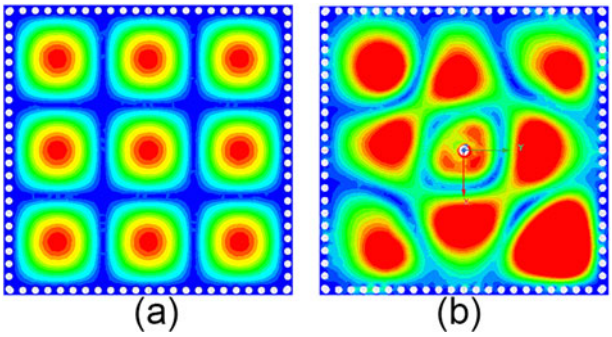

Figure 3. Electric field distribution at 39 GHz: (a) before etching slots and (b) after etching slots.

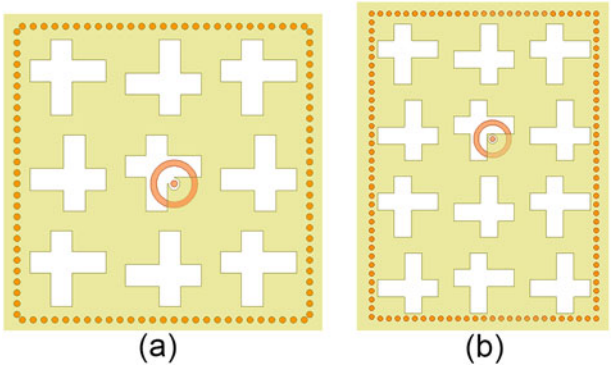

Figure 4. Subarray structures: (a) 3×3 and (b) 3×4.

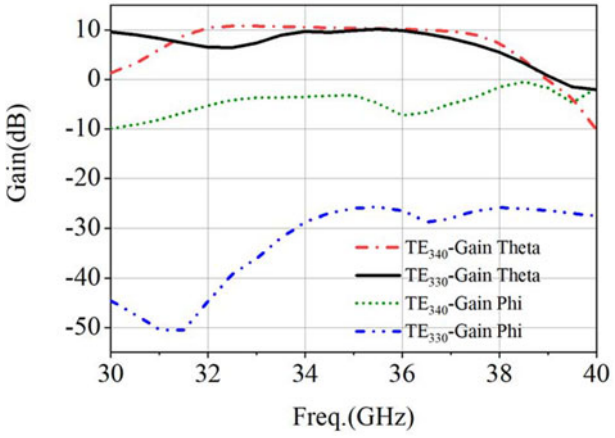

Figure 5. Radiation performance of the subarray of different resonant modes.

The antenna subarrays are arranged in two ways, 3×3 and 3×4. The size of the resonant cavity is calculated using (1), (2), and (3), as shown in Fig. 4. The offset of the feeding position, the size of the etching gap, and the offset value are kept consistent. From the simulation gain results of the E-plane (Phi = 45°) in Fig. 5, it can be seen that the antenna excited by TE_{330} mode has more advantages in XPD than the antenna excited by TE_{340} mode. In conclusion, for the 45° linearly polarized antenna in this paper, the cavity size has a significant impact on XPD. A square cavity can better form the 45° linearly polarized wave due to the consistent size of the metal walls, while the shape of a rectangular cavity can reduce the XPD. It is worth mentioning that when using an HOM cavity to achieve

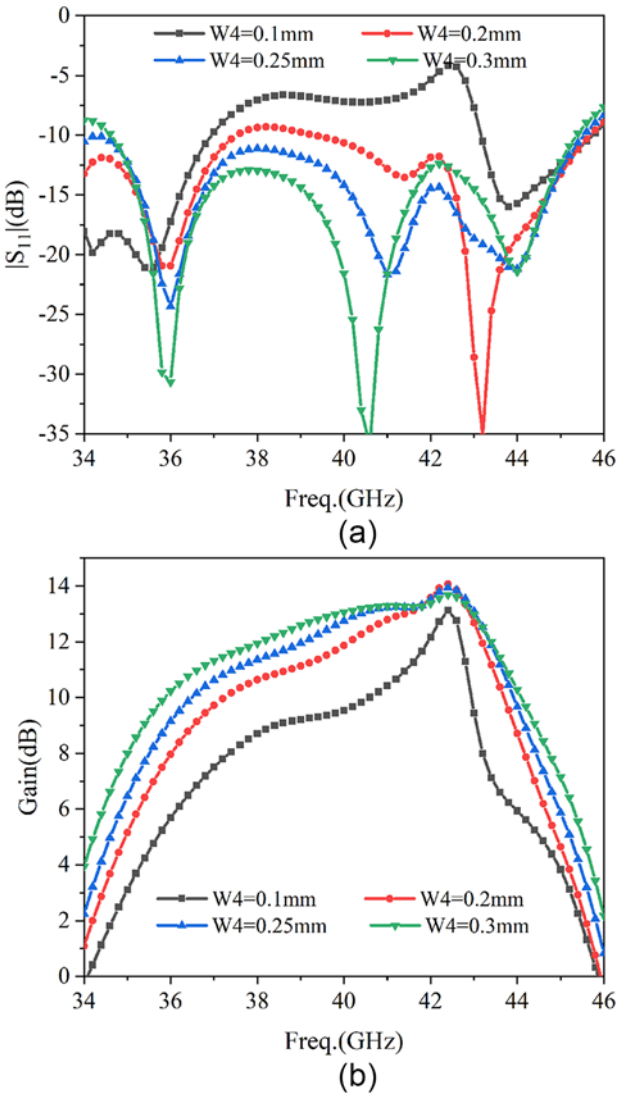

Figure 6. The influence of the slots offset of W4 on subarray performance: (a) *S*-parameter and (b) gain.

a compact design, we aim to use a single feed port to excite as many radiation slots as possible. On the other hand, we want to maintain a wide bandwidth. However, as the mode order increases, the bandwidth of the antenna decreases. This is because higher-order modes are more sensitive to the cavity size. Therefore, there is a trade-off between mode order and bandwidth.

In addition, W4 is the offset dimension between the center of the transverse slot and the center of the longitudinal slot. As depicted in Fig. 6, when W4 varies between 0.1 mm, 0.2 mm, 0.25 mm, and 0.3 mm, it is evident that both the antenna matching bandwidth and the gain increase with increasing W4. To ensure the impedance bandwidth ($|S_{11}| \leq -10$ dB) of the antenna, the value of W4 is chosen as 0.25mm.

R2 is the size of concentric circle etching on the outer side of the probe in the metal layer. It can be seen from Fig. 7 that when the antenna presents an upper metal electrical contact, R2 = R1 = 0.2 mm, it can be seen that the matching situation of the antenna is much worse than that without an electrical contact. In summary, electrical contact can cause impedance matching to deteriorate, and as the R2 increases, impedance matching will deteriorate,

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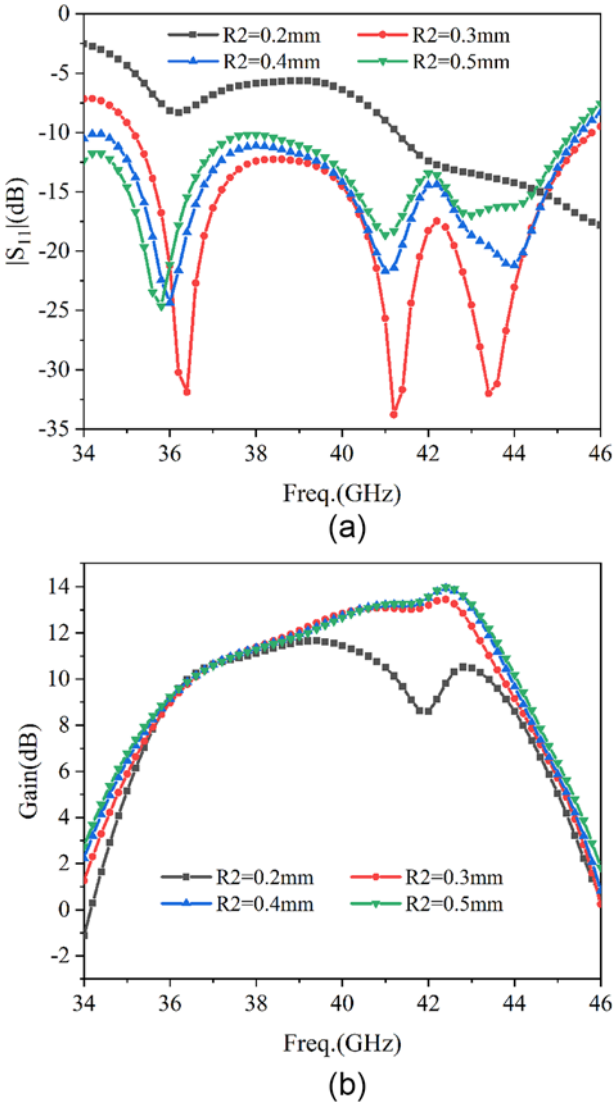

Figure 7. The influence of the R2 on subarray performance: (a) *S*-parameter and (b) gain.

Table 1. Dimensions of the subarray in millimeters.

Parameter	L1	L2	L3	W1	W2
Values	10.8	3	3	10.8	1.2
Parameter	W3	W4	R1	R2	R3
Values	1.2	0.25	0.2	0.4	0.81

resulting in an increase in low-frequency bandwidth. Therefore, selecting an appropriate etching size can effectively improve the working bandwidth of the antenna. So the value of R2 is chosen to be 0.4 mm.

The detailed parameters are shown in Table 1 with values in millimeters. The simulated results of the proposed 45° subarray are given in Fig. 8. As shown in Fig. 8, the subarray can achieve an impedance bandwidth of 27.8% (34.4–45.53 GHz) and a 3-dB gain bandwidth of 17.1% (36.88–43.76 GHz). The maximum gain is 13.5 dBi.

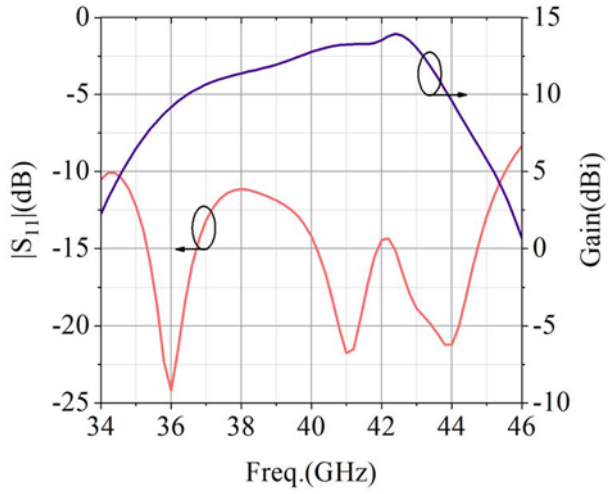

Figure 8. The S-parameter and peak gains in the broadside direction of the subarray antenna.

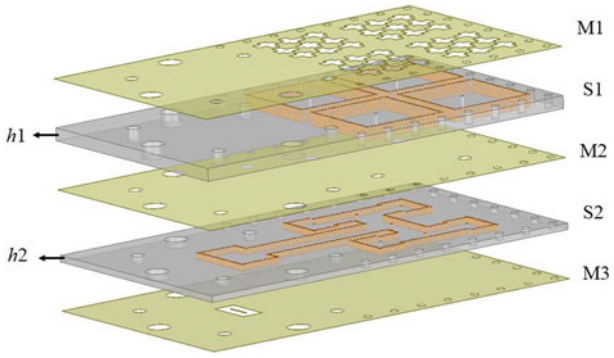

Figure 9. 3D exploded view of the proposed antenna array ($h1 = 1.515$ mm, $h2 = 0.787$ mm).

6×6 array design

Array design

Based on the structure of the proposed subarray, an exploded view of a 6×6 antenna array is shown in Fig. 9. Two PCB layers are used for array construction. The upper layer consists of 2×2 subarrays, with a spacing of 13.2 mm between each two subarrays. Figure 10(a) shows the feed network of the proposed antenna for TE_{330} mode excitation. The feed network is fed by a WR-22 waveguide, and a conversion to the probe (shown in Fig. 10(b)) is used at the end to feed the subarray. The substrate of the feeding network layer is Rogers 5880 with a thickness of 0.787 mm. As shown in Fig. 10(c), the simulated −15 dB $|S_{11}|$ bandwidths of the feed network and the transition structure cover 36–43.5 GHz. The transmission loss of the feednetwork is 0.16 dB, and the maximum difference among $|S_{12}|$, $|S_{13}|$, $|S_{14}|$, and $|S_{15}|$ is below 0.44 dB within the operation bandwidth.

In the M2 layer, a larger concentric circle at the location of the probe is etched for better impedance matching. The part outside the cavity is loaded with through holes for mounting screws, in order to reduce the performance deteriation caused by the air gap between two PCBs. The feeding network design parameters and values are shown in Fig. 10.

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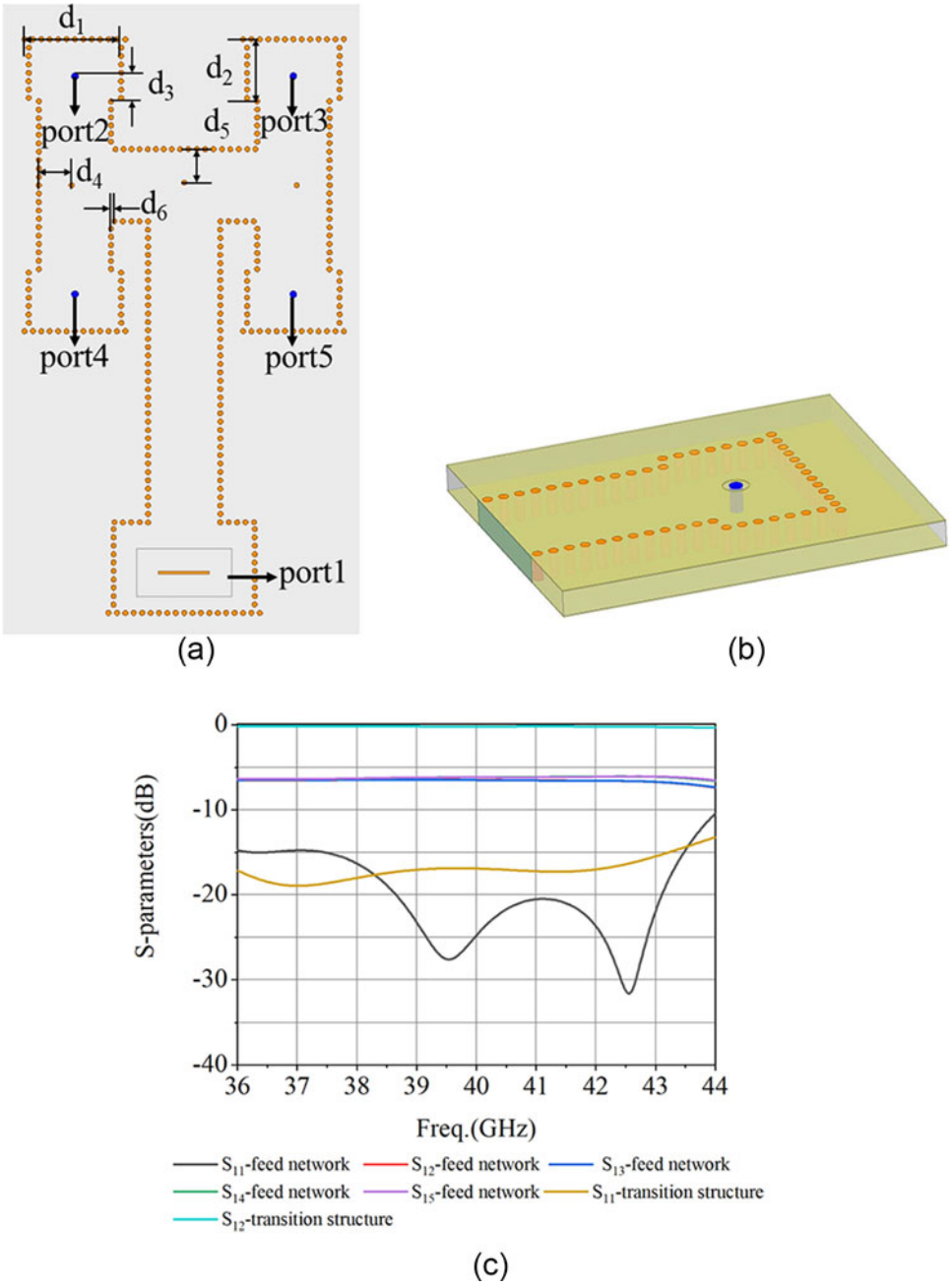

Figure 10. (a) Structure of the feed network for TE_{330} mode. (b) Transition structure from SIW to probe. (c) Their properties in simulations ($d1 = 5.5$ mm, $d2 = 3.83$ mm, $d3 = 1.7$ mm, $d4 = d5 = 1.8$ mm, $d6 = 0.2$ mm).

Results and discussion

Figure 11 shows the images of the 6×6 antenna array prototype and the array in the test environment. The antenna was fabricated using standard PCB technology. The antenna array has the dimensions of 53 mm×30 mm×2.432 mm and the aperture area of 21.6 mm×21.6 mm surrounded by screw holes for assembly. In Fig. 12(a), the simulated and measured *S*-parameters of the 6×6 antenna array for $|S_{11}| \leq -10$ dB are 15.3% (36.89–43 GHz) and 13.9% (36.98–42.52 GHz), respectively.

The antenna was measured using a spherical near-field measurement system. In Fig. 12(b), the simulated and measured peak gain is 19.06 dBi and 19.3 dBi, respectively. The simulated 3-dB gain bandwidth is 16.02% (36.85–43.31 GHz), and the measured one is 13.6% (37–42.4 GHz). The measured aperture efficiency is 88.1% at 38.5 GHz, and the average measured aperture efficiency is 66.9%. The simulated radiation efficiencies are above 86.5% within the impedance bandwidth, and the maximum radiation efficiency can reach 91.7% at 39 GHz. The average measured radiation efficiency is 75%. The discrepancies in the measured results are due to the fact that the antenna test environment is not ideal, in which the placement and the test accuracy need to be improved.

The simulated and measured radiation patterns in $-90^\circ < \theta < 90^\circ$ are given in Fig. 13. The XPD levels in the maximum radiation

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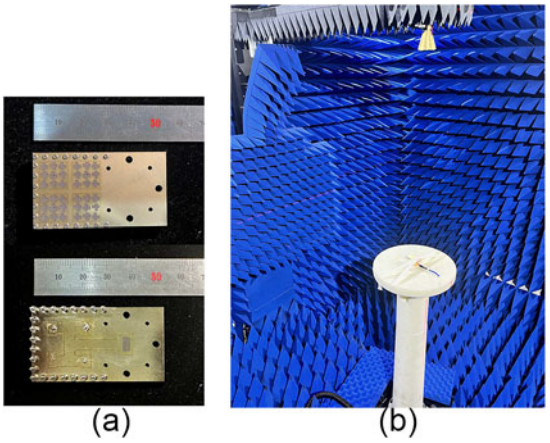

Figure 11. (a) The image of the fabricated prototype. (b) Measurement environment of the antenna.

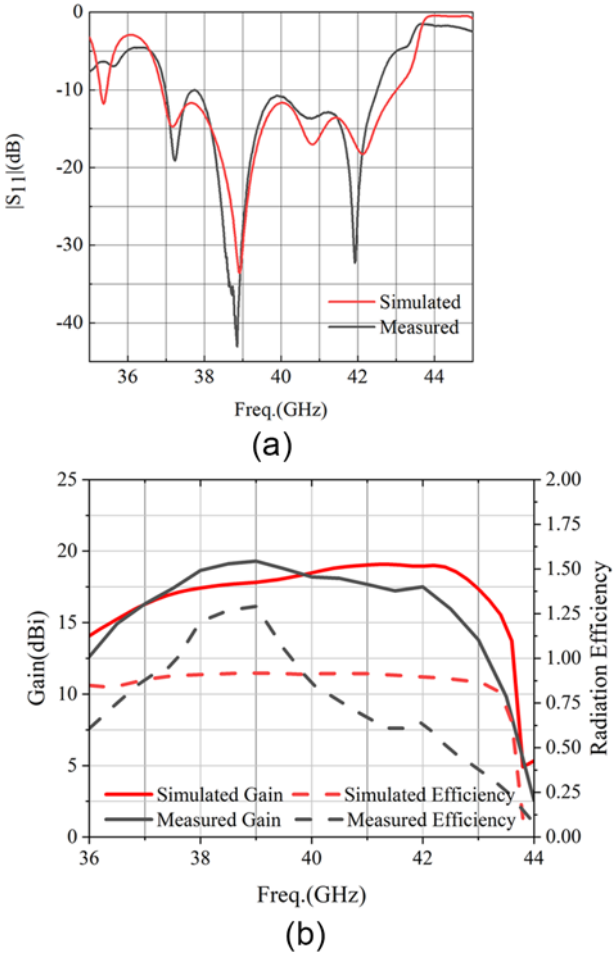

Figure 12. Measured and simulated results of the antenna array. (a) $|S_{11}|$ and (b) gain and radiation efficiency.

direction are higher than 30 dB at 38, 40, and 42 GHz, indicating good 45° linear polarization characteristic.

There are many papers that aimed at the 45° linear polarized antenna, and a comparison is made in Table 2. Compared to other SIW technology-based 45° linearly polarized antennas, the proposed antenna etching asymmetric cross slots on the top layer of

Table 2. Comparision with other 45° LP antennas

Ref.	Antenna type	Freq. (GHz)	IBW (%)	Peak gain (dBi)	RE (%)	AE (%)	No. of elements	Total size (λ^3)	XPD (dB)
[15]	SIW + DR	35	6.25	13.55	85	49.7	1×8	6.31×8.42×0.618	N.A.
[19]	SIW + patch	34.5	9.71	14.1	98.9*	91.5	1×7	4.65×3.34×0.284	20
[21]	SIW + patch	79	10.6	17.2	52.4	N.A.	2×8	N.A.×N.A.×0.067	<20
[22]	SIW + rod	60	13.2	17.5	N.A.	49.9	4×4	3.2×2.8×5.1(CS)	18
[23]	HW + slot	28.5	31.58	26.1	88.8	87.7	8×8	7.03×7.03×1.748	45.8
[24]	HW + slot	28	18.8	25	71.7	61	8×8	7.02×7.02×0.933	31.3
This paper	SIW + slot	39	13.9	19.3	75#	66.9#	6×6	6.89×3.9×0.316	30

IBW: relative impedance bandwidth; RE: radiation efficiency; AE: aperture efficiency; XPD: cross-polarization discrimination level at $\theta = 0°$; HW: hollow-waveguide; DR: dielectric resonator; *: simulated results; N.A.: not apply; CS: cavity size; #:Average value within the working band

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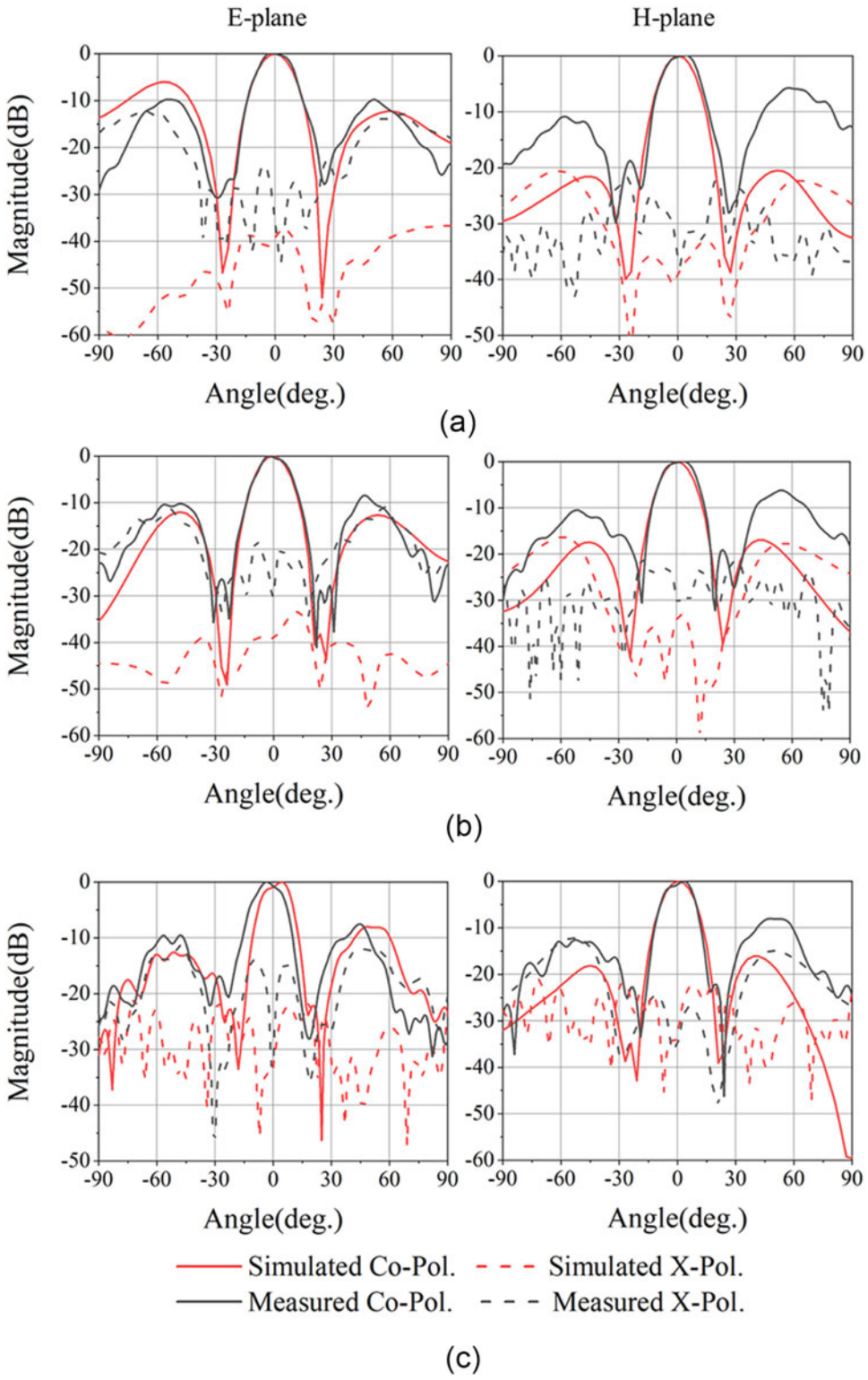

Figure 13. Simulated and measured radiation patterns in E-plane ($\phi = 45^{\circ}$) and H-plane ($\phi = 135^{\circ}$): (a) 38 GHz, (b) 40 GHz, and (c) 42 GHz.

HOM cavity is more dominant in terms of bandwidth and XDP level, which is better than that in [15, 19, 21] and is comparable to that in [22]. However, [22] has a wide impedance bandwidth at the expense of the profile. Meanwhile, [23] and [24] are slot array antennas fed by hollow-waveguide, which have wide impedance bandwidths and high XPD levels, but the profiles are higher than the proposed antenna. What is more, the radiation efficiency is higher than that in [24].

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Conclusion

In this paper, a wideband and high XPD level 45° linearly polarized antenna array has been designed. Asymmetric orthogonal slots etched on the top of the high-order mode cavity contributes to low profile and wide bandwidth. Compared to the waveguide-fed antenna, the proposed antenna has the advantages in profile and radiation efficiency. In conclusion, the characteristics of the 45° linear polarized antenna show more potential in 5G communications.

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Competing interests. The author(s) declare none.

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