



60-GHz Double-Layer Transmitarray Antenna Using Complementary Structure

Wenxing An¹, Xiaochi Zhang¹, Yu Luo^{1*}, Jian Wang^{1*} and Lin Xiong²

¹The Tianjin Key Laboratory of Imaging and Sensing Microelectronic Technology, School of Microelectronics, Tianjin University, Tianjin, China, ²The Department of Electronic Engineering, Tsinghua University, Beijing, China

Abstract—A novel double-layer transmitarray element is presented at 60 GHz with linearly- and circularly-polarized characteristics. A planar frequency-selective structure using the complementary design is adopted to augment the element performance for millimeter-wave applications. By integrating two different types of structure, i.e. cross and slot type, the compensation phase range is extended effectively with a satisfactory transmission magnitude. A transmitarray prototype is fabricated and tested to verify this double-layer complementary design. The measured gain at 60.5 GHz is 33.1 dBi with an aperture efficiency of 42.15%. Low side-lobe and cross-polarization levels are obtained. The proposed double-layer complementary design can reduce the structure complexity effectively and offer a high aperture efficiency at a low cost, which can be a potential candidate for the millimeter-wave transmitarray.

Keywords: high gain, double-layer, transmitarray, antenna, millimeter (MM) wave

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*Correspondence:

Yu Luo
yluo@tju.edu.cn
Jian Wang
wangjian16@tju.edu.cn

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1 INTRODUCTION

Recently, transmitarray antenna has become a popular research item. Compared with the traditional lens antenna, the transmitarray aperture can be a planar frequency-selective surface, which makes it easy integration, visual invisibility, and economical fabrication with PCB technology. Many transmitarray antennas have been investigated with diverse performances such as wideband [1], multiple bands [2], low profile [3], multiple beams [4], and beam scanning [5].

Many devices have been reported for the millimeter-wave band near 60 GHz [6–8]. A three-layer linearly polarized transmitarray antenna was presented in [9] for millimeter-wave applications. Employing a slot-coupling method, a triple-layer linearly polarized transmitarray was proposed in [10]. Although satisfactory performances have been realized, these designs have at least three metallic layers that make the structure relatively complicated. A dual-layer transmitarray was proposed for the 77-GHz automotive radar applications [11]. However, the proposed element can only provide 0° and 180° phase differences, which would result in a relatively large phase error and lower aperture efficiency. A dual linearly polarized transmitarray was presented at D-band with a peak gain of 32 dBi and aperture efficiency of 32% at 150 GHz [12]. It is discussed in [13] that at least three metallic layers are required to achieve a compensation phase range of nearly 360° and -1-dB magnitude simultaneously. To reduce the structural complexity, the double-layer element has been investigated and reported. A double-layer transmitarray element with metallic vias was proposed [14, 15]. It was further investigated in [16–18] with improved performance. A two-layer linearly-polarized metal-only TA was presented in [19].

For the 60-GHz millimeter-wave and even higher frequency band, transmitarrays with a simple structure are desired for easy fabrication and low cost. Then, some double-layer designs without vias

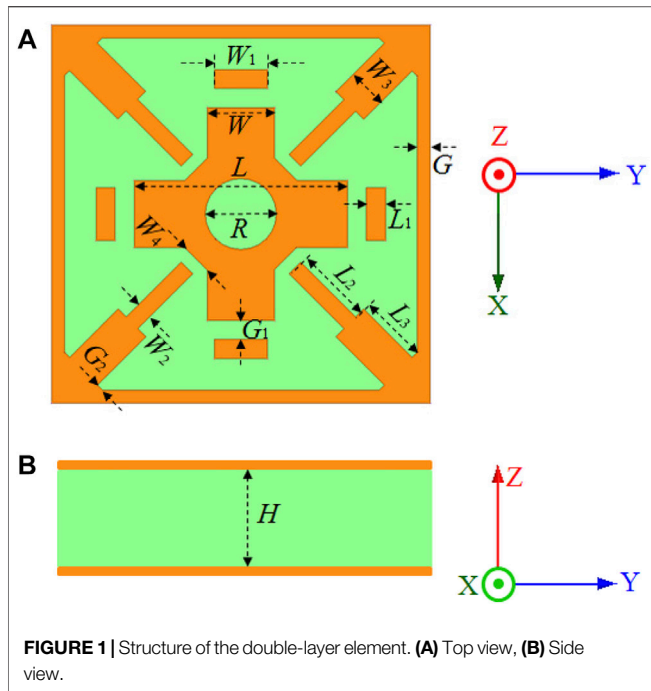


FIGURE 1 | Structure of the double-layer element. **(A)** Top view, **(B)** Side view.

are investigated. A double-layer planar lens antenna was presented in [20] using a gradient metasurface structure with a measured aperture efficiency of 24.6%. A double-layer design from [21] can achieve a high aperture efficiency of 60.2% using a circular polarization conversion approach for circular polarization. Recently, a conformal transmitarray was developed in [22] using a dual-layer Huygens element with single linear polarization. It has a measured gain of 20.6 dBi with an aperture efficiency of 47%. Although the above designs have achieved satisfactory performance, it is still difficult to accommodate both linear and circular polarizations simultaneously to meet the application requirements of different occasions. Recently, a planar transmitarray element based on a complementary frequency-selective structure was reported in [23] with an extended compensation phase range. It can be adapted potentially for millimeter-wave applications.

A complementary double-layer transmitarray element is presented for the millimeter-wave band in this letter. The element performance is improved effectively based on the hybrid design combining cross and slot-type structures with linear and circular polarization characteristics. Then, a transmitarray antenna is fabricated for verification. Satisfactory radiation performance has been achieved with a measured gain of 33.1 dBi. The measured aperture efficiency is 42.15% with low side-lobe and cross-polarization levels.

2 PROPOSED DOUBLE-LAYER COMPLEMENTARY ELEMENT

The double-layer complementary element is shown in **Figure 1**. The element size is 2.98 mm in the X- and Y-directions. Two

TABLE 1 | Antenna element parameters (mm).

Para	L1	W	W1	W2	W2	W3	W4
Value	0.15	0.53	0.42	0.13	0.13	0.31	0.25
Para	G	G1	G2				
Value	0.1	0.15	0.057				

identical metallic structures are printed on the top and bottom of the Rogers-5880 substrate with a thickness of 20 mil. The detailed parameters are in **Table 1**.

The metallic structure consists of modified cross, slot, and parasitic structures. The slot-type structure has four stubs at the corners with lengths L_2 , L_3 , and widths W_2 , W_3 . The cross has the length L and width W with a circular slot carved at the center. Four parasitic rectangular patches with the sizes of L_1 and W_1 are distributed around the cross with a gap of G_1 . All metallic structures are distributed symmetrically. The central symmetry structure makes it suitable for both linear and circular polarizations.

Using structural design freedom, two complementary elements with different stub and cross sizes are utilized to extend the compensation phase range, as shown in **Figure 2**. For element 1, the stub is relatively short with $L_2 = 0.37$ mm and $L_3 = 0.05$ mm, respectively. The diameter of the central slot is with the equation $D = -1.75L_2 + 4.52L - 2.17$. The phase range is obtained by changing the cross length L from 0.9 to 1.67 mm. For element 2, the stub lengths L_2 and L_3 are 0.61 and 0.54 mm, respectively. D is with the equation of $D = (1.96 \text{ mm} - L) \times 2$. The L varies between 1.68 and 1.9 mm. The element performances with a normal incidence at 60 GHz are plotted in **Figure 2**. The phase range of element 1 is from -59° to -141° with a transmission magnitude better than -1.5 dB. For element 2, the -1.5 -dB phase range is from 40° to 133° . The phase range between -180° and 180° can be covered with a maximum phase error of 55° based on these two elements. So a double-layer complementary element with an

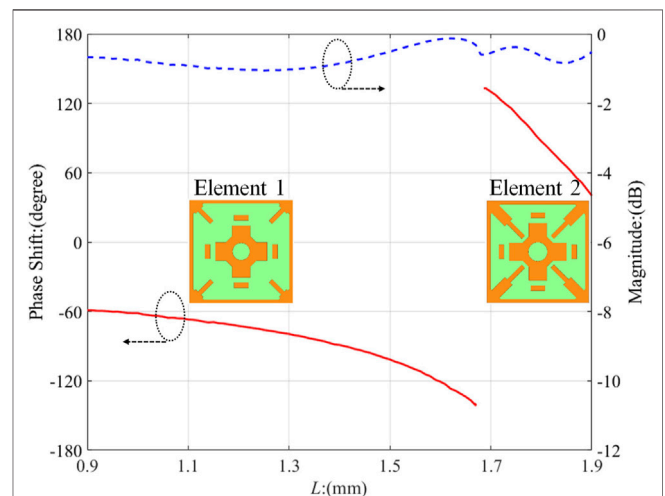
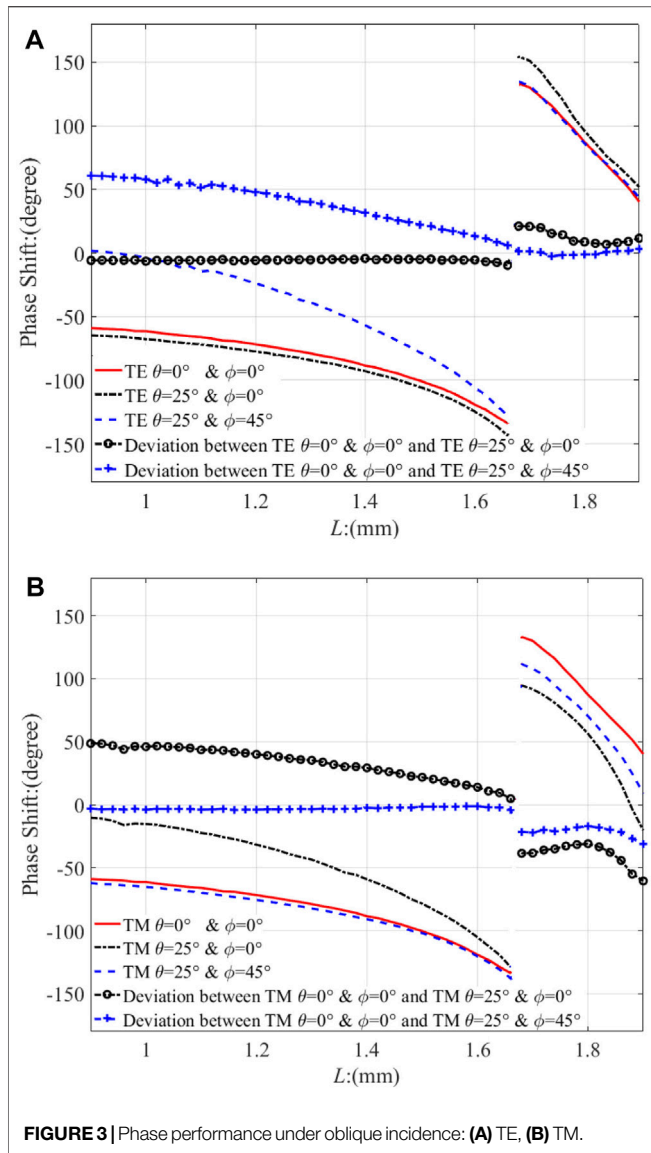


FIGURE 2 | Phase and magnitude performance of the complementary element at 60 GHz with normal incidence.



extended phase range is realized for the 60-GHz millimeter-wave band.

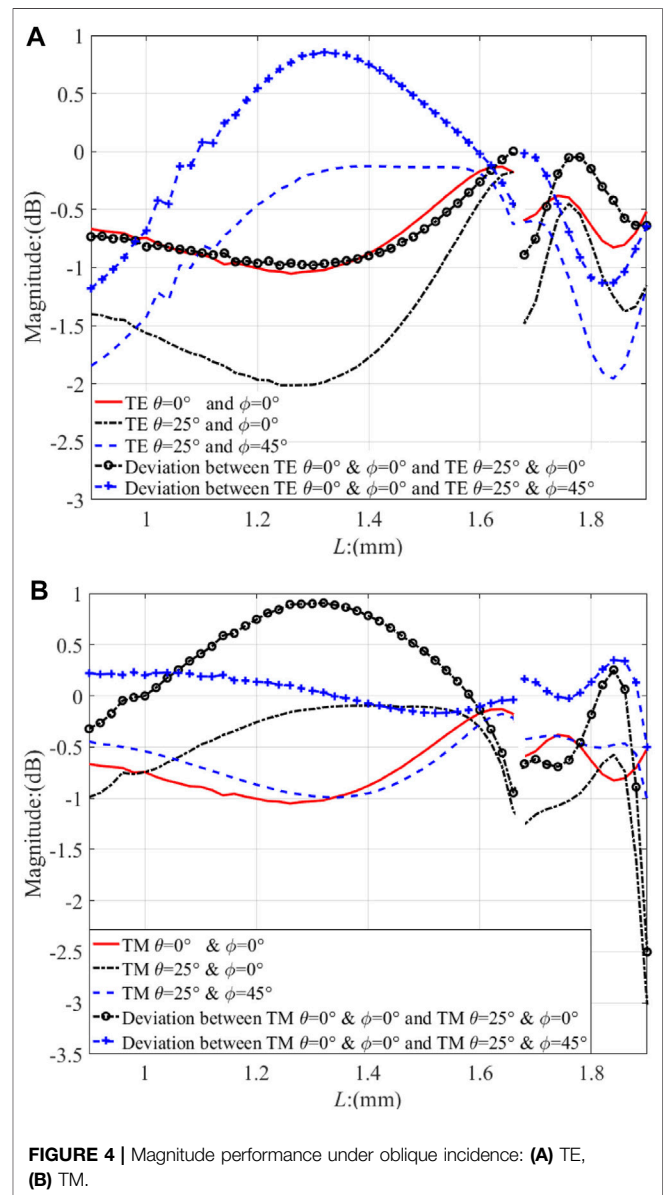
3 ANTENNA ANALYSIS

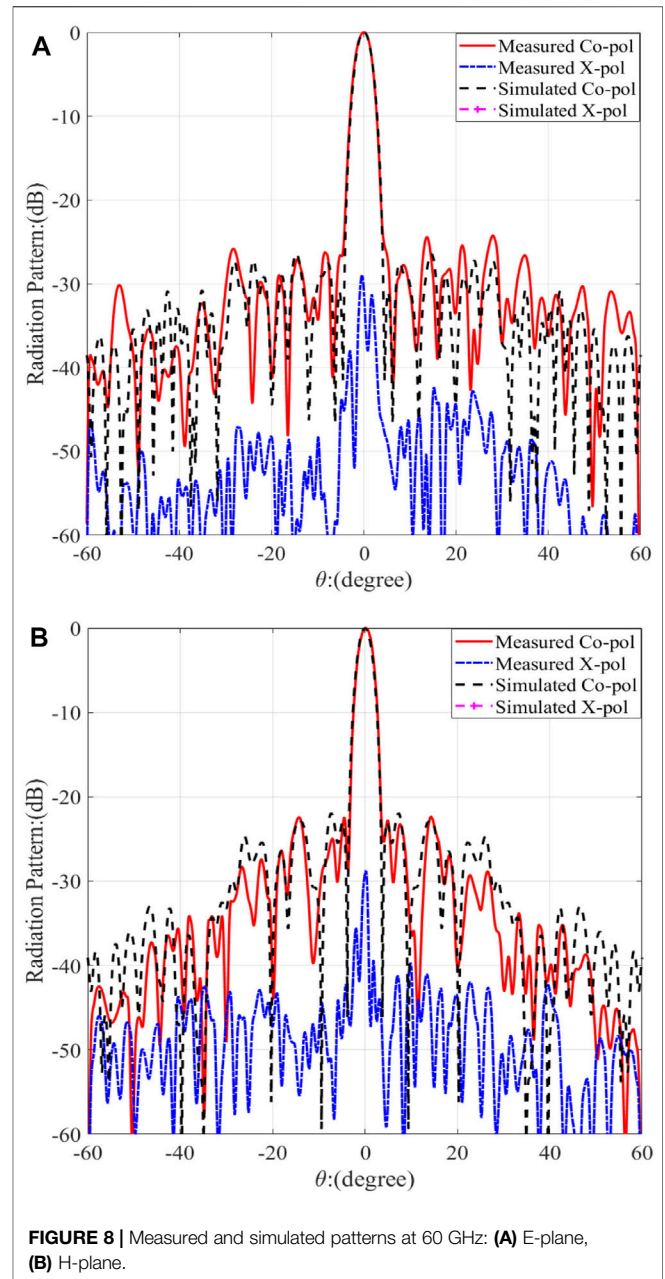
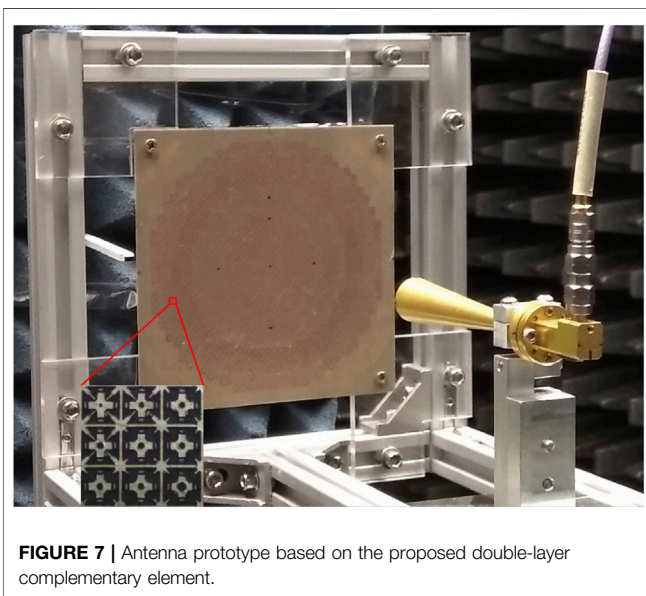
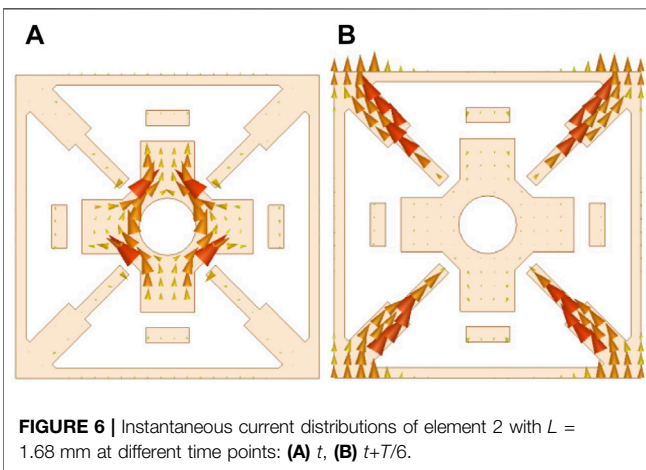
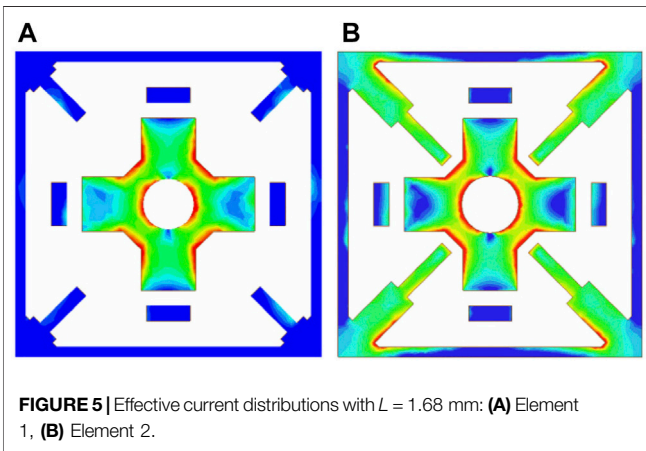
The element performances under oblique incidence are simulated with the TE and TM sources. The phase and magnitude performances are plotted in Figure 3 and 4. It is observed in Figure 3A that the maximum phase error for TE source is 61° between the normal and oblique incidence with $\theta = 25^\circ$ and $\phi = 45^\circ$. For the TM source in Figure 3B, the maximum phase error is 49° between the normal and oblique incidence with $\theta = 25^\circ$ and $\phi = 0^\circ$. In Figure 4, the maximum magnitude error for TE source is -1.18 dB between the normal and oblique incidence with $\theta = 25^\circ$ and $\phi = 45^\circ$ while the maximum magnitude error for TM source is -2.5 dB between the normal and oblique incidence with $\theta = 25^\circ$ and $\phi = 0^\circ$.

As elements 1 and 2 can cover the phase ranges from -180° to 0° and from 0° to 180° respectively, the effective current distributions are plotted for analysis, which is depicted in Figure 5 with the cross length $L = 1.68$ mm.

For element 1, it is observed in Figure 5A that most currents distribute on the cross while there are few currents on the slot-type structure due to a relatively small stub length. The slot-type structure has little effect on the element performance when the stub length is electrically small, so the slot-type structure has limited influence on element 1.

In Figure 5B, the currents are on cross and slot-type structures of element 2. The slot-type structure affects the element performance when the stub length is comparable to the wavelength. The instantaneous current distributions are in Figure 6. The cross is excited at the reference time point of t in Figure 6A. The slot-type structure is excited at the time point





of $t + T/6$ in **Figure 6B** where T represents one cycle. It is noticed that the slot-type and cross structures are not excited simultaneously but with a time interval of $T/6$. The introduced slot-type structure can offer an extra phase shift compared with element 1, so the transmission phase is shifted from the negative range to the positive range, as shown in **Figure 2**. It can be concluded that the cross is responsible for the performance of element 1. Both the cross and slot-type structures affect the performance of element 2. They are stimulated successively within half cycle.

TABLE 2 | Comparison of the proposed antenna with existing designs.

References	Freq. (GHz)	No. of layers	Polariza-tion	Gain (dBi)	Aperture effi. (%)	3-dB-gain Bandwidth
[9]	61.5	3	Linear	32.5	42.7	21%
[10]	61	3	Linear	33.4	48	15.4%
[11]	76.5	2	Linear	24.1	19.3	N. A
[12]	150	3	Linear & Circular	32	32	19.8
This work	60.5	2	Linear & Circular	33.1	42.15	5.9%

4 EXPERIMENTAL VERIFICATION

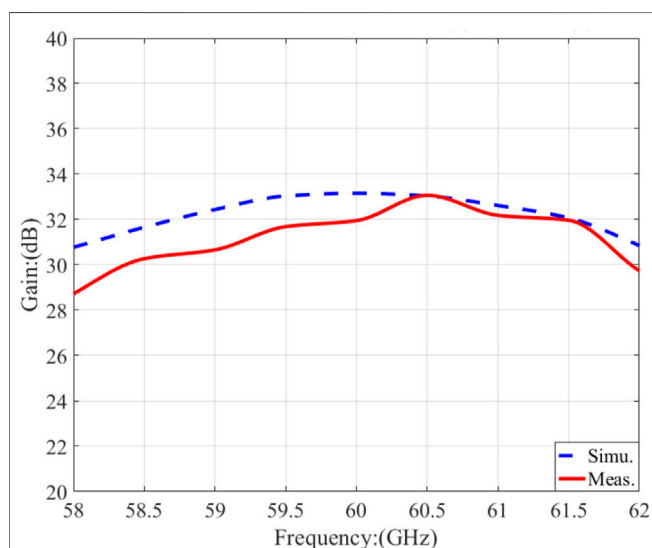
To verify the proposed double-layer frequency-selective structure, a transmitarray antenna with a diameter of 113 mm is designed and fabricated, as shown in **Figure 7**. It includes 1,060 elements with a cross length varying between 0.9 and 1.89 mm. A linearly-polarized horn antenna with a gain of 18.25 dBi at 60 GHz is employed to illuminate the antenna aperture in the normal direction. The height is optimized to be 140 mm. Based on the element and feed characteristics, the compensation phase of each element is calculated [24]. A full-wave simulation is conducted using CST software. The calculated radiation patterns are plotted in **Figure 8**. In **Figure 9**, the antenna gain at 60 GHz is calculated to be 33.16 dBi with the simulated aperture efficiency of 43.7% [25].

An LPKF ProtoLaser system is employed for the aperture fabrication while the antenna prototype is assembled and tested in an anechoic chamber. The measured radiation patterns and gain are plotted in **Figures 8, 9**, respectively. The measured gain at 60 GHz is 31.95 dBi with an aperture efficiency of 34.5% while the maximum gain is 33.1 dBi at 60.5 GHz with an aperture efficiency of 42.15%. The 3-dB-gain bandwidth is from 58.4 to 61.9 GHz with a relative bandwidth of 5.9%. It is observed in **Figure 8** that the measured

main beam almost overlaps with the simulation result. The measured side-lobe levels are below -24.2 dB at E-plane and -22.3 dB at H-plane while the maximum cross-polarization level is -29.1 dB. It is observed that the measured gain is 1.2 dB lower than the simulated one at 60 GHz while the simulated and measured gains are almost equal at 60.5 GHz.

There are certain discrepancies between the simulation and measurement results. Firstly, certain elements are not etched precisely. It would introduce additional phase and magnitude errors. Secondly, the transmitarray prototype is assembled manually, the assembly errors with the radiation aperture and feeding horn are inevitable. Finally, the antenna is supported by a metallic frame. It would introduce more reflections and refractions, resulting in certain influences on the radiation patterns.

The proposed transmitarray is compared with some existing millimeter-wave designs in **Table 2**. Based on the traditional three-layer frequency-selective structure [9, 10], aperture efficiency of more than 42% has been realized with 3-dB-gain bandwidths of more than 15%. However, they are only suitable for linear-polarized applications with a relatively complex structure. A linearly-polarized dual-layer transmitarray was proposed [11] at 77 GHz with a relatively lower aperture efficiency of 19.3%. A triple-layer transmitarray antenna has been presented at D-band with both linear and circular polarization characteristics [12]. The measured gain is 32 dBi with an aperture efficiency of 32%. To improve the aperture efficiency and to reduce the structural complexity, a double-layer complementary frequency-selective structure is designed in this work. The measured aperture efficiency is improved to be 42.15%, which is close to the triple-layer designs of [9, 10]. Furthermore, the proposed element is suitable for linear and circular polarizations. It can fulfill various requirements and extend its application scenarios.

**FIGURE 9** | Measured and simulated gains.

5 CONCLUSION

A double-layer complementary transmitarray structure is studied at 60 GHz for linear and circular polarizations. Combining the cross and slot-type structure, a double-layer frequency-selective element has been designed with good transmission phase and magnitude performances. The working principle of this complementary structure has been investigated and a prototype has been fabricated for verification. The measured antenna gain is 33.1 dB at 60.5 GHz with an aperture efficiency of 42.15%. The antenna structural complexity and cost have been reduced effectively. With these favorable advantages, this double-layer transmitarray antenna should have broad application prospects in the future.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

WA prepared the idea and the original manuscript. XZ conducted the simulation and measurement, YL provided

the instruction. LX provided and optimized. JW provided the fabrication and final manuscript.

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