Dual-Linearly-Polarized Printed Dual-Dipole Antenna Array for Polarimetric Radar Application

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***Abstract*— This paper presents a dual-linearly-polarized printed dual-dipole antenna array and its application in polarimetric radar systems. For verification, a prototype of a 5×5 antenna array with a three-dimensional (3D) feeding circuit for S-band is designed, fabricated, and tested. The three-dimensional feeding circuit includes horizontal and vertical feeding sub-circuits. Mortise and tenon joints are used in the substrates of the vertical and horizontal feeding sub-circuits to facilitate assembly and soldering. According to the 5×5 prototype array, the half-power beamwidth is about 20°, the average gain is 16.1 dBi and gain variation is within ±0.8 dB for the *x*-polarized sub-array, while the average gain is 15.75 dBi and gain variation is within ±0.75 dB for the *y*-polarized sub-array throughout the desired operating band. The efficiency is larger than 60% for the *x*-polarized sub-array and is larger than 69% for the *y*-polarized sub-array, respectively.**

Keywords—antenna array, polarimetric, dual-polarization, 3-D power distribution network

I. INTRODUCTION

Target identification has always been a popular research topic for military applications for a while. It refers to the use of radar to transmit and receive signals, especially when the eyes cannot observe due to factors such as long distance and dim sky. Then it interprets the signals to estimate the information of the target. Compared with the information that a single-polarized antenna can transmit or receive, a dual-polarized antenna can obtain more parameters. Then through post-processing calculations, it can obtain the characteristic parameters of invariant properties of polarization and more structural details of the target. Therefore, an antenna with dual polarization is necessary and will greatly improve the accuracy of the radar system.

Synthetic aperture radar (SAR) is one of the dual-polarized antenna systems which are widely used in remote sensing, diagnostic analysis, and target detection and identification. SAR is typically mounted on a moving platform such as an aircraft or spacecraft, to scan objects which are fixed on the ground. Furthermore, its application is different from an antenna that is installed on the ground to detect moving objects. Another way of identifying targets is to use a polarimetric radar system, which is used to detect the location of the target and obtain information on what the target is. The polarimetric radar system can not only detect the scattering characteristics of the target by sending and receiving two orthogonally polarized electromagnetic (EM) waves, but can also detect the interaction between the two polarized EM waves.

To improve the polarimetric radar system, a proposed design concept of an antenna array with feeding circuit will be extended theoretically. In this paper, a prototype of a 5×5 dual-linearly-polarized printed dual-dipole antenna array with three-dimensional feeding circuit is designed, fabricated, and tested.

This paper is organized into five sections. In Section II, the antenna design considerations are presented, including antenna units, 5×5 antenna array, and the design details of the antenna array feeding circuit. Simulation and measurement results for a prototype of antenna array are presented in Section III, and Section IV concludes this paper.

II. ANTENNA ARRAY DESIGN CONSIDERATIONS

A. Printed Dual-Dipole Antenna Unit

In this work, the structure of the antenna unit is based on the antenna structure proposed in [2]-[3]. The unit cell is composed of two parallel center-fed folded-dipoles connected in parallel by coplanar strip (CPS) sections on the back of the dielectric substrate and is fed by a T-shaped coupling structure on the front side of the substrate. The T-shaped structure with the two open-ended symmetric lateral arms serve as a balun. The pair of CPS sections with a stepped width is designed for impedance matching. The unwanted radiation associated with the T-shaped coupling structure will be cancelled out because of the structural symmetry of the entire antenna. Therefore, one of the major advantages of the proposed T-shaped coupling structure is the inherently lower cross-polarization level. In order to achieve a dual-linearly-polarized antenna array, we use two antennas with an angle difference of 90 degrees to create two orthogonal radiated signals. They are shown in Fig. 1 with its detailed parameters of the two antenna units listed in Table I.

B. 5×5 Dual-Polarization Antenna Array

For the polarimetric radar application, the prototype is a 5×5 dual polarization radar array as shown in Fig. 2. In the figure, all the x-polarized antenna units are in black and are identical to each other, while all the y-polarized antenna units are in gray and are identical to each other. The center-to-center spacing between adjacent antenna units along the x-axis and y-axis are denoted as *dx* and *dy*, respectively. The choice of inter-element spacing *dx* and *dy* is limited by the size of the antenna unit. Additionally, the spacing between two nearest antenna units of the same polarization direction, i.e. *2dx* and *2dy*, must be less than one wavelength to avoid the presence of grating lobes. Thus, the best choice for *dx* and *dy* is 40 mm.

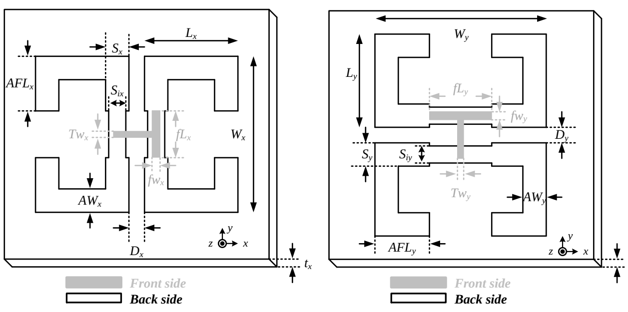


Fig. 1. Configuration and dimensions of the printed dual-dipole (a) x-polarized and (b) y-polarized antenna. (Units: mm)

TABLE I

PARAMETERS FOR TWO ANTENNA UNITS (UNIT: MM)

Parameters	*x*-polarized antenna	Parameters	*y*-polarized antenna
W_x	33	W_y	32
L_x	18	L_y	17
S_x	5	S_y	4
S_{ix}	3	S_{iy}	3
AW_x	4	AW_y	4
D_x	2	D_y	3
t_x	1.6	t_y	1.6
fw_x	1.2	fw_y	1.2
fL_x	19	fL_y	19
Tw_x	1.4	Tw_y	2
AFL_x	9	AFL_y	9

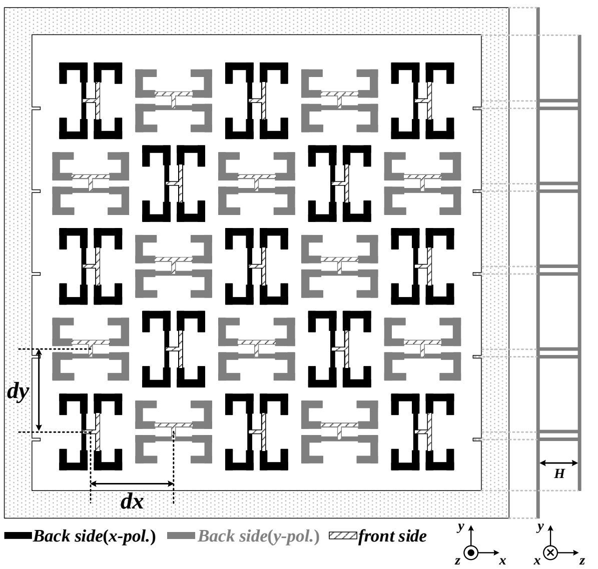


Fig. 2. Configuration of the 5×5 dual-polarization antenna array.

C. 3-D Feeding Circuit Design for the 5×5 Array

The 3D feeding circuit is composed of vertical feeding sub-circuits and a horizontal feeding sub-circuit. The height of the substrate of a vertical feeding sub-circuit, *H*, which also is the distance from the antenna array to the horizontal feeding circuit substrate, is close to a quarter wavelength of the desired frequency, which is 20 mm. The 5×5 dual polarization antenna array can be divided into five 5×1 linear sub-arrays. Each 5×1 linear sub-array consists of either three x-polarized antenna units and two y-polarized antenna units or two x-polarized antenna units and three y-polarized antenna units. The role of the vertical feeding sub-circuits is to divide the input signal into two or three, depending on the antenna units to be fed. In each 5×1 linear sub-array, there are two vertical feeding sub-circuits placed in parallel, each responsible for the two different polarization antenna units. One is for x-polarized antenna units, and the other is for y-polarized antenna units. Therefore, ten total boards of vertical feeding sub-circuits are needed in the entire 5×5 array. The horizontal feeding sub-circuit separates the respective input signals for the x-polarized and y-polarized antenna units and divides each input signal into five parts for the five linear sub-arrays. The ground plane of the horizontal feeding circuit can also be used as the reflector of the array. Moreover, mortise and tenon joints are used in the substrates of the ten vertical and one horizontal feeding sub-circuits to facilitate assembly and soldering.

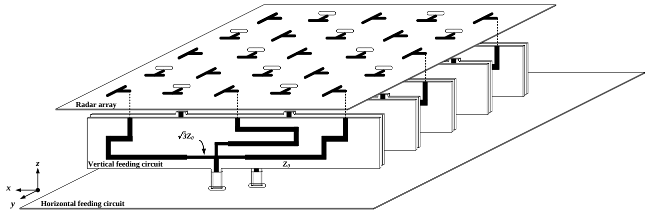


Fig. 3. 3D figure of 5×5 polarimetric radar.

Fig. 4 shows the feeding network for the x-polarized antenna. For the vertical feeding sub-circuit of the three-element x-polarized linear sub-array, there is a tenon tongue on the vertical feeding sub-circuit substrate and a mortise hole on the horizontal feeding sub-circuit substrate. First, consider the row with the 5×1 linear sub-array with three x-polarized antenna units and two y-polarized antenna units. To feed the three x-polarized antenna units, a three-way power divider is formed by three branches, each with an identical signal trace length of 120 mm and a $\sqrt{3}Z_0$ quarter wave transformer, where Z0 is the characteristic impedance. Subsequently, when looking at the row with the 5×1 linear sub-array with two x-polarized antenna units and three y-polarized antenna units, in order to feed the two x-polarized antenna units, a two-way power divider is formed by two branches, each with an identical signal trace length of 80 mm and a $\sqrt{2}Z_0$ quarter wave transformer. In the half of the horizontal feeding sub-circuit for the x-polarized antenna, a five-way power divider is initially divided into three output branches, two of which are formed by $\sqrt{13/5}\,Z_0$ quarter wave transformers and one with a $\sqrt{13/3}\,Z_0$ quarter wave transformer. For the first and third branch, it has an additional two-way power divider which is formed by $\sqrt{5/3}\,Z_0$ and $\sqrt{5/2}\,Z_0$ quarter wave transformers, respectively. The difference in the total path lengths of the first and second vertical feeding sub-circuits of x-polarized antenna units is 40 mm. Thus, a 40-mm long delay line is needed and introduced in the routing of the second output branch of the horizontal feeding sub-circuit. Furthermore, the difference in the total path lengths of the first and third vertical feeding sub-circuits of x-polarized antenna units is 80 mm, so an 80-mm long delay line is needed and introduced in the routing of the third output branch of the horizontal feeding sub-circuit.

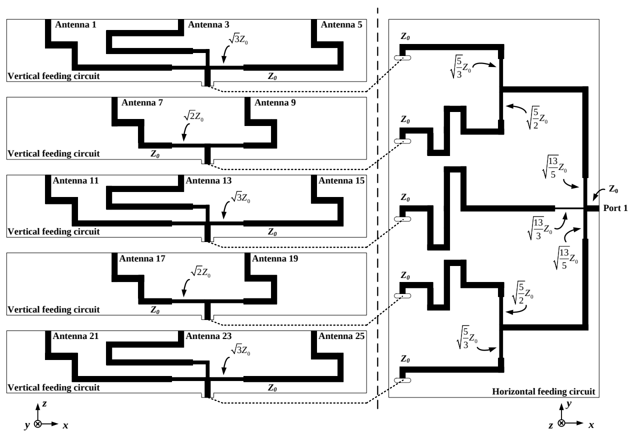


Fig. 4. Feeding network for x-polarized antenna.

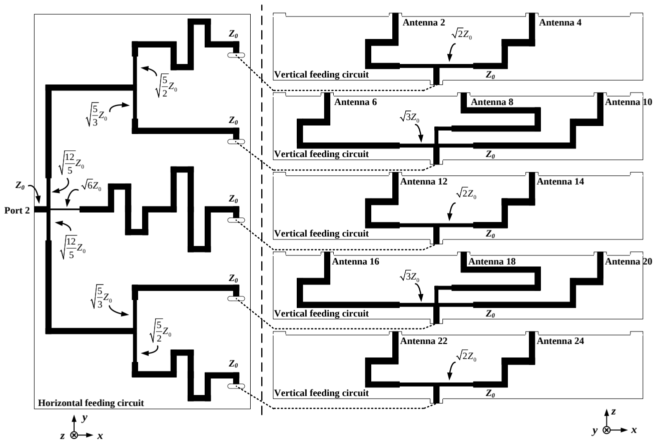


Fig. 5. Feeding network for y-polarized antenna.

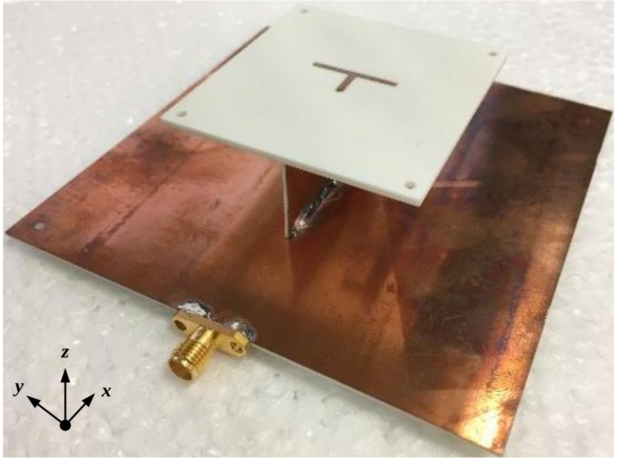


Fig. 6. Figure of the x-polarized printed dual-dipole antenna unit.

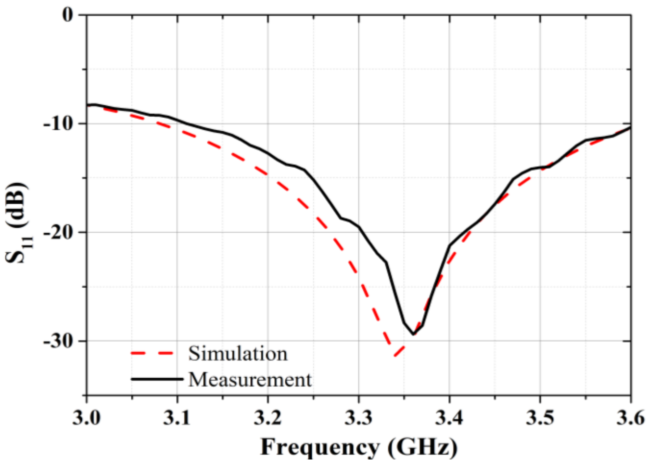


Fig. 7. Simulated and measured |S11| of the x-polarized antenna.

Similarly, when considering the horizontal feeding sub-circuit for the y-polarized antenna, another five-way power divider is also initially divided into three output branches, two of which are formed by $\sqrt{12/5}\,Z_0$ quarter wave transformers and one with a $\sqrt{6}Z_0$ quarter wave transformer. For the first and third branches, it has an additional two-way power divider which is formed by $\sqrt{5/2}\,Z_0$ and $\sqrt{5/3}\,Z_0$ quarter wave transformers, respectively. The difference in the total path lengths of the first and second vertical feeding sub-circuits of y-polarized antenna units is also 40 mm as shown in Fig. 5. Therefore, a 40-mm long delay line is introduced in the routing of the first output branch of the horizontal feeding sub-circuit for the y-polarized sub-array. Moreover, the difference in the total path lengths of the second and third vertical feeding sub-circuits of y-polarized antenna units is 120 mm, so a 120-mm long delay line is needed and introduced in the routing of the center output branch, which is realized by cascading two sections of delay lines of 40 mm and 80 mm.

The first main feature of the proposed 3D feeding circuit is that the N×N array feeding structure was simplified by using 2N parallel pieces of vertical feeding sub-circuits. Another feature is that the mortise hole design is adopted in the antenna array substrate and the horizontal feeding sub-circuit substrate, while, the tenon tongue design is used in the vertical feeding sub-circuit substrates to facilitate the array assembly and soldering. A third feature is that the feeding signals for the x-polarized and y-polarized antenna units are separated in the horizontal feeding sub-circuit, and then fed through the associated vertical feeding sub-circuits. The final main feature of this 3D feeding circuit is that if the array is a $2^n \times 2^n$ radar array, a large antenna array can be implemented because the feeding signal can be divided by additional two-way power dividers.

III. Simulation and Measurement Results

A. *Antenna unit*

For the antenna unit, the input signal is fed via an SMA connector at the edge of the reflector. The signal travels through a horizontal 50-Ω microstrip line. Its signal trace lies beneath the reflector with a dielectric substrate in between. The trace then travels through a vertical 50-Ω microstrip line implemented on a PCB that is vertically placed on the reflector plane, as shown in Fig. 6. After entering the antenna terminals, the signal is divided into two by the T-shaped structure, and the signals travel respectively to the dipole radiators through the coplanar strip (CPS) line. Fig. 7 shows the |S11| responses of the x-polarized antenna unit. The simulated bandwidth is 16% from 3.08 GHz to 3.62 GHz for |S11| < -10 dB, and the measured bandwidth is 14.9% from 3.11 GHz to 3.61 GHz.

Fig. 8 and Fig. 10 show the radiation patterns of the x-polarized and y-polarized antenna unit at 3.3 GHz, respectively. Fig. 9 shows the gain and efficiency of the x-polarized antenna unit. The gain of a single unit is larger than 7 dBi, and its variation remains within ±1 dB in the concerned band. Fig. 11 shows the gain and efficiency of the y-polarized antenna unit. The gain of a single unit is larger than 7.7 dBi, and its variation also remains within ±1 dB in

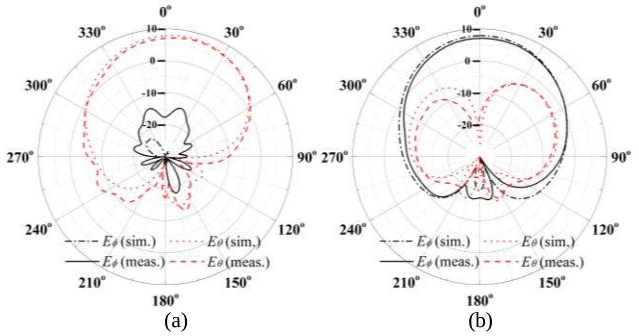


Fig. 8. Simulated and measured radiation patterns of x-polarized unit at 3.3 GHz (unit: dBi). (a) x-z plane and (b) y-z plane patterns.

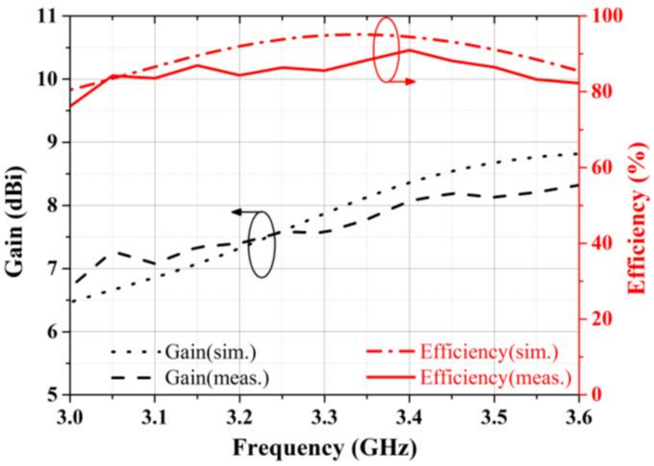
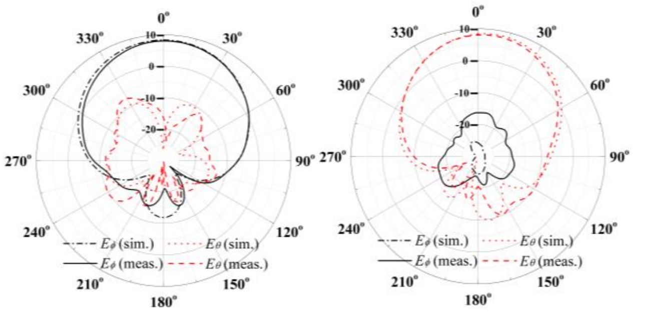


Fig. 9. Simulated and measured antenna gain and radiation efficiency of the x-polarized unit.



(a) (b)

Fig. 10. Simulated and measured radiation patterns of y-polarized unit at 3.3 GHz (unit: dBi). (a) x-z plane and (b) y-z plane patterns.

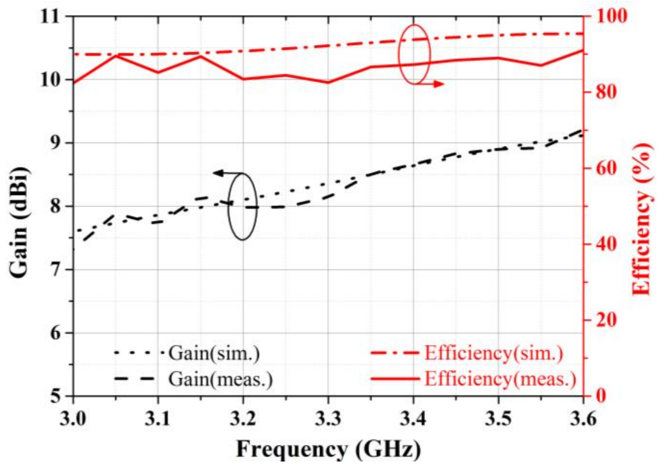
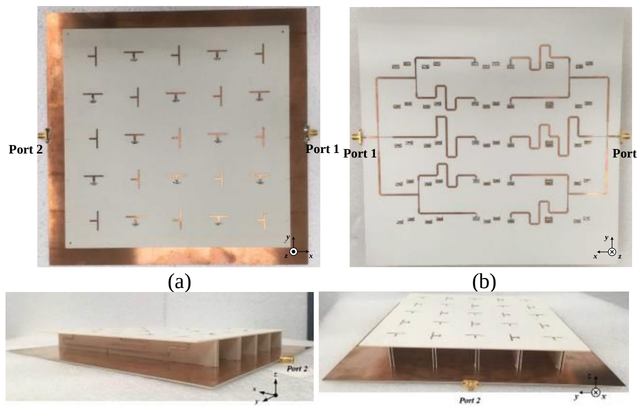


Fig. 11. Simulated and measured antenna gain and radiation efficiency of the y-polarized unit.



(a) (b) (c) (d)

Fig. 12. (a) Top, (b) bottom, (c) and (d) side views of the prototype antenna.

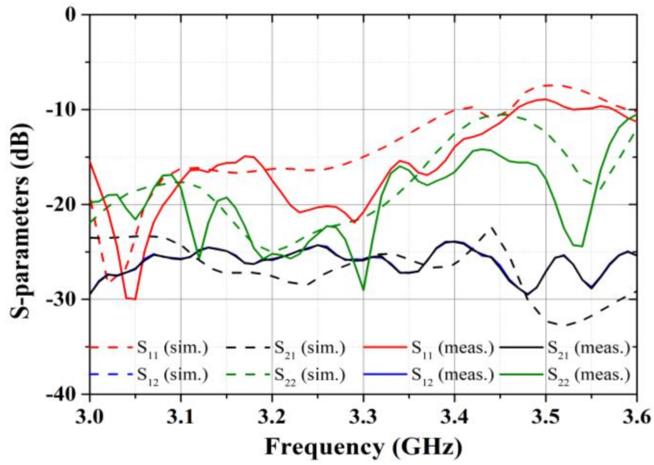


Fig. 13. Simulated and measured S-parameters of the prototype antenna.

the concerned band. As the frequency increases, the gain also increases because the effect of the two dipole's array factor increases the directivity. The efficiency of the x-polarized and y-polarized antenna unit are both larger than 82% in the concerned band.

B. 5×5 polarimetric radar

In our HFSS simulations and measurements, Rogers RO4003C is used as the substrate of the antenna array, vertical, and horizontal feeding sub-circuits. The SMA connector is also taken into consideration. In Fig. 12(a), the SMA connector on the right-hand side is port 1 which is for feeding the x-polarized antenna units and the left-hand side is port 2 which is for the y-polarized antenna units. There are ten total vertical feeding sub-circuits in the whole array, five for x-polarized antenna units and the other five for y-polarized antenna units. Fig. 13 shows the S-parameters of the 5×5 dual polarization antenna array. Port 1 is for excitation of x-polarized antenna units, while port 2 is for the excitation of y-polarized antenna units. At both port 1 and port 2, the design specifications are for an operating bandwidth of 3.1 GHz to 3.5 GHz with reflection coefficient lower than -10 dB and an isolation better than 25 dB within the desired bandwidth.

Fig. 14 and Fig. 15 show the radiation patterns of the x-polarized antenna sub-array and y-polarized antenna sub-array at 3.3 GHz, respectively. The simulated and measured patterns agree well with each other. The half-power beamwidth of the radiation patterns are about 20 degrees and the side-lobe level are less than -10 dB. As for the gain and efficiency of the 5×5 dual polarization antenna array, Fig. 16 and Fig. 17 shows the results of the x-polarized and y-polarized sub-arrays, respectively. When estimating the total efficiency of the 5×5 dual polarization antenna array with the feeding circuit, we need to consider both the efficiency of the antenna array itself, and the efficiency of the feeding circuit. For the standalone array, the simulated efficiency is about 87%, while for the feeding circuit, the simulated efficiency is about 80%. Thus, the total efficiency of the entire array, including the array and feeding circuit, is estimated to be about 70%. As shown in Fig. 16, for the x-polarized sub-array, the average gain is 16.1 dBi and gain variation is within ±0.8 dB throughout the desired operating

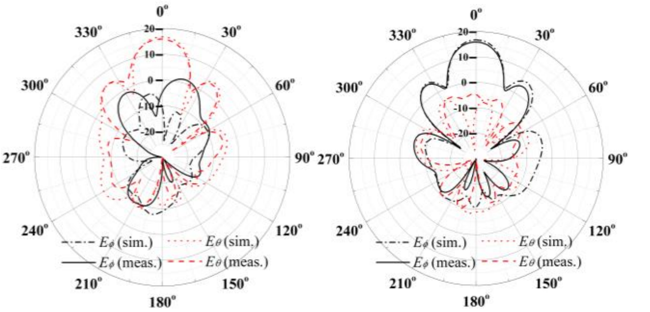


Fig. 14. Simulated and measured radiation patterns of x-polarized dipole excitation at 3.3 GHz (unit: dBi). (a) x-z plane and (b) y-z plane patterns.

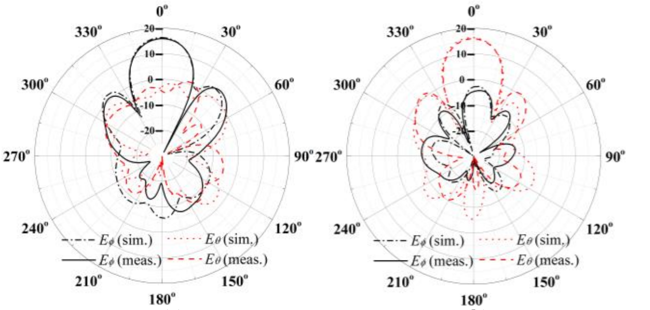


Fig. 15. Simulated and measured radiation patterns of y-polarized dipole excitation at 3.3 GHz (unit: dBi). (a) x-z plane and (b) y-z plane patterns.

band. The efficiency is larger than 60% in the desired band. As shown in Fig. 17, for the y-polarized sub-array, the average gain is 15.75 dBi and gain variation is within ±0.75 dB throughout the desired operating band. The efficiency is larger than 69% in the desired band.

In summary, the proposed array design with very minimal in-band gain variation is suitable for use in polarimetric radar systems. According to the 5×5 prototype array presented above, the half-power beamwidth is about 20°, and the total efficiency is greater than 60%. The peak gain can readily be increased by extending the proposed design concept to a larger array.

IV. Conclusion

This work proposes a dual-linearly-polarized printed dual-dipole antenna array with a 3-D feeding circuit for polarimetric radar system applications. X-polarization and y-polarization signals are fed into individual five-way power dividers, to then send the signals to the folded-dipole antenna units through vertical sub-circuits. A 5×5 dual-polarization antenna array has been realized with its x-polarized sub-array having a gain of 16.1±0.8 dB and over 60% efficiency; and the y-polarized sub-array having a gain of 15.75±0.75 dB, with over 69% efficiency for the entire operating band.

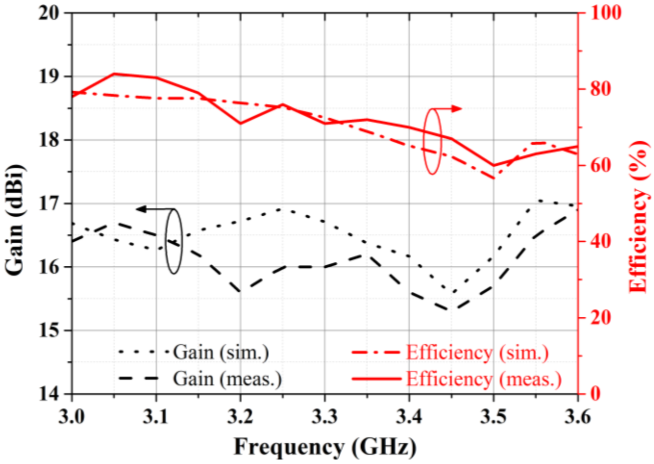


Fig. 16. Simulated and measured antenna gain and radiation efficiency of the prototype antenna when x-polarized antenna excitation only.

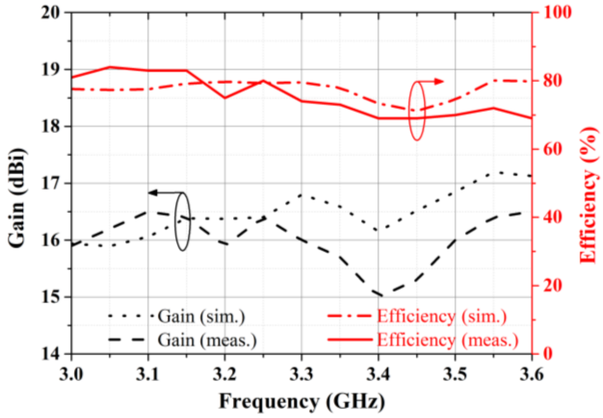


Fig. 17. Simulated and measured antenna gain and radiation efficiency of the prototype antenna when 7-polarized antenna excitation only.

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