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An Efficiency-Improved Tightly Coupled Dipole Reflectarray Antenna Using Variant-Coupling-Capacitance Method

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ABSTRACT In this paper, a tightly coupled dipole reflectarray antenna as well as a variant-coupling-capacitance method to improve the antenna aperture efficiency is presented. Tightly coupled elements and true-time-delay lines are employed in the design of a wideband reflectarray. The proposed reflectarray can operate from 2 GHz to 5 GHz with the gain varying from 11.3 dBi to 21 dBi. Moreover, we propose a variant-coupling-capacitance method to improve the reflectarray aperture efficiency at lower frequency. By changing the coupling capacitance between neighboring elements according to their positions in the reflecting surface, a more linear equivalent distance delay line is achieved. Hence, phase error is reduced. According to measurement, the reflectarray gain in 2 GHz using the proposed method is increased by 3 dBi compared with the previous design. Aperture efficiency in 2 GHz is improved by 21.6%.

INDEX TERMS Reflectarray, tightly coupled antenna, wideband, variant coupling capacitance.

I. INTRODUCTION

Reflectarray (RA) antennas are a new generation of high-gain antennas thanks to their distinguishable electrical and mechanical characteristics. RA antennas combine merits of both reflectors and printed arrays as well as offering alternative design with low profile and low mass features [1], [2]. In comparison with reflector antennas, RA antennas are easy to manufacture and install due to their flat structures. Compared with printed arrays, RA antennas eliminate the loss from feedline networks and phase adjustment networks as reflectarray has usually one feed antenna, and the elements embed phase altering structures to achieve plane wave on the aperture surface [3].

Although RA antennas outweigh many kinds of antennas in terms of various favorable features, they suffer from the disadvantage of narrow bandwidth. The main factors that restrain bandwidth are the bandwidth of the reflectarray elements and the differential spatial phase delay [4]. Many approaches have been adopted to broaden the bandwidth. In terms of improving the unit cell bandwidth performance,

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multi-resonant elements [5], [6], multilayer elements [2], [7], spline shaped unit cell [8], and subwavelength element [9] are employed. In order to compensate the differential spatial phase delay caused by different paths from the feed to different elements, true-time-delay techniques are used in [10], [11]. Besides these methods, a phase synthesis approach is developed to increase bandwidth independent of the element frequency behavior [12].

Recently another approach proposed by [13] utilizes tightly coupled dipole reflectarray elements to increase bandwidth to a great extent. Tightly coupled antenna is first proposed by Ben Munk [14] based on Wheeler's current sheet theory [15]. The coupling capacitance between elements is exploited to improve bandwidth performance. Researchers from Kent University firstly applied tightly coupled theory into reflectarray design and achieved the bandwidth of 103%. Besides reflectarray, tightly coupled elements are also utilized to design transmitarrays [16].

In this paper, we present a tightly coupled dipole reflectarray antenna (TCdra). Section II demonstrates the design basis of a TCdra. The proposed TCdra operates from 2 GHz to 5 GHz with the gain varying from 11.3 dBi to 21 dBi. However, though the reflectarray has a wider

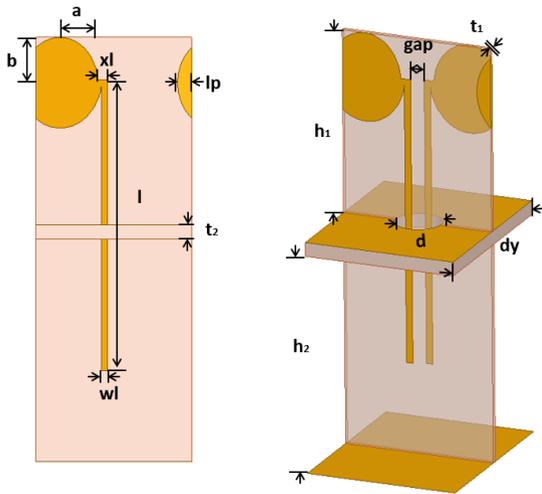


FIGURE 1. Configuration of the reflectarray element.

bandwidth than most of the existed reflectarrays, in lower frequency the gain is relatively low. This is because in lower frequency the behaviors of the reflecting elements deviate from the designed value and phase error becomes greater. Therefore, in Section III we propose a variant-coupling-capacitance (VCC) method to increase the gain in lower frequency. By changing the coupling capacitance between neighboring unit cells according to their positions in the reflecting surface, the linearity of phase delay line improves in the objective frequency. And the difference between the objective frequency design line and the ultimate design line is reduced. As a result, the objective frequency gain is increased. The model is simulated and fabricated to verify the design. Measurement results in Section IV show that the variant-coupling-capacitance tightly coupled dipole reflectarray antenna (VTCDDRA) gain is increased by 3 dBi in 2 GHz. The modified antenna gain varies from 14.4 dBi to 21.9 dBi within the working frequency of 2 GHz to 5 GHz. The cross polarization discrimination is higher than 20 dB.

II. TIGHTLY COUPLED REFLECTARRAY ELEMENT DESIGN

A. ELEMENT DESIGN

The tightly coupled reflectarray element in [13] is consisted of a wideband dipole (bowtie dipole) and a pair of true-time-delay (TTD) lines. Following this design guideline, we use elliptical dipole and TTD lines as wideband array element and spatial phase distribution structure respectively. The configuration of the element is shown in Fig. 1. The dipole element is printed on both sides of the substrate with a TTD line connected to each dipole arm. The element is placed perpendicular to the ground plane.

Firstly, we choose suitable geometry of the elliptical dipole which in this design the long axis of the dipole is 0.11λ (λ is center frequency wavelength). The TTD line width is designed to match the impedance of the dipole. The distance between the element and ground plane is the main factor

that decides the bandwidth and we optimize h_1 to obtain maximum bandwidth. However, some of the elements require large spatial phase delay which means that the corresponding TTD line is longer than the distance between the elements and ground plane. So we open a hole on the ground to let the line go through and add a second ground plane. In tightly coupled phase array, the mutual coupling is achieved by compact configuration or inter-element capacitance. In this paper the coupling strength is controlled by adjusting the overlapping distance of the dipole arms. We investigate the element reflection phase versus frequency of different coupling capacitance (lp) in Fig. 2. When the TTD line is relatively short ($l = 1$), the reflection phase hardly changes as lp increases. When the TTD line is in a medium range ($l = 13$), with the same increment of lp , the delayed phase is mildly enlarged. When l reaches relatively big value ($l = 20$), the amount of delayed phase is increased greatly in lower frequency whilst staying nearly unchanged in higher frequency.

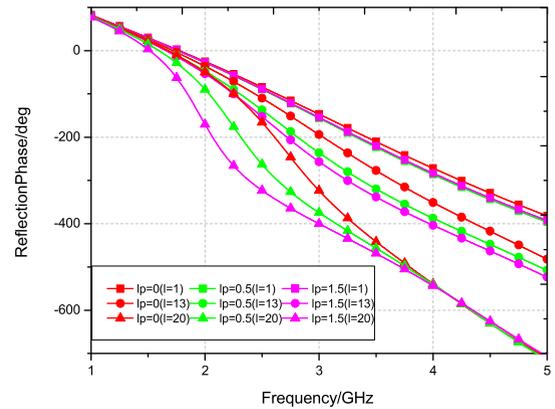


FIGURE 2. The effect of lp (unit: mm) on the reflection phase of different TTD line length (unit: mm).

Eventually we optimize lp as well as other parameters to obtain a maximum operating bandwidth. All parameters of the element are shown in table 1. Fig. 3 illustrates element reflection coefficients of different TTD line length. The fairly

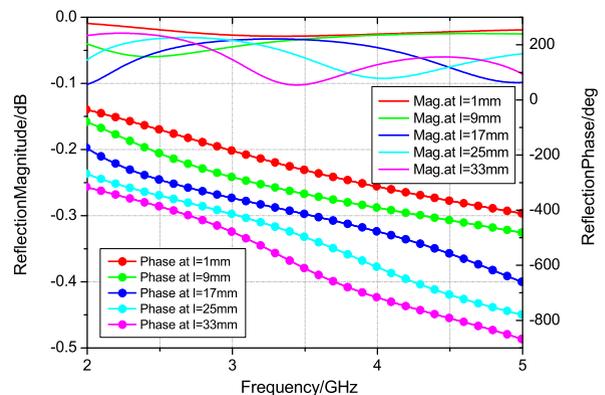


FIGURE 3. Reflection coefficients of different l .

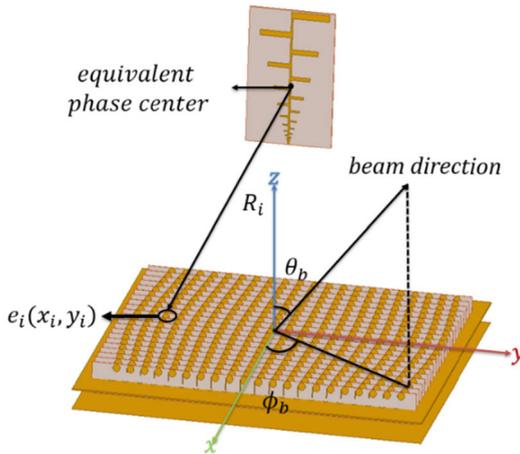


FIGURE 4. Configuration of reflectarray antenna.

linear reflection phase in a wide frequency range indicates wideband property.

B. EQUIVALENT DISTANCE DELAY DESIGN

The sketch of the reflectarray is shown in Fig. 4. In a reflectarray, the phase delay equation is described as follows:

$$\varphi_{e_i}(x_i, y_i) = -k_0 \sin \theta_b (x_i \cos \phi_b + y_i \sin \phi_b) + k_0 R_i \quad (1)$$

e_i is the i th element, (x_i, y_i) is the position of in the reflecting surface, (θ_b, ϕ_b) is the direction of the beam, φ_{e_i} is the required phase delay of e_i , R_i is the distance between the phase center of the feed and e_i , k_0 is space propagation constant. Let (1) be divided by k_0 and let $\varphi_{e_i}/k_0 = d_{e_i}$, then

$$d_{e_i} = -\sin \theta_b (x_i \cos \phi_b + y_i \sin \phi_b) + R_i \quad (2)$$

$$d_i = d_{e_i} - d_{e_1} \quad (3)$$

In (3), d_i is the equivalent distance delay of e_i [13]. If one reflectarray element is able to keep its equivalent distance delay unchanged in a frequency band, it means the reflectarray element can precisely compensate differential spatial phase delay in this frequency band. Equivalent distance delay as a function of TTD line length l of different frequencies is obtained through simulation and is shown in Fig. 5 in solid line with asterisks. $d_f(l)$ denotes equivalent distance delay versus l at frequency f . $d(l)$ denotes the designed equivalent distance delay in all frequencies. Using $d(l)$ derived from (4) to design reflectarray element can minimize phase error overall [14].

$$\sum_{f=f_l}^{f_h} [d_f(l) - d(l)]^2 = \min \quad (4)$$

III. VARIANT-COUPPLING-CAPACITANCE METHOD

A. METHOD DEMONSTRATION

The equivalent distance delay lines in 3 GHz, 4 GHz and 5 GHz have good linearity, and are close to the designed line $d(l)$. But $d_{2GHz}(l)$ gradually deviates from $d(l)$ as l

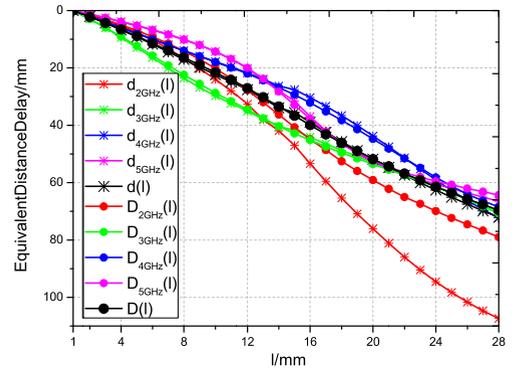


FIGURE 5. Equivalent distance delay line comparison between traditional reflectarray ($d_f(l)$) and improved reflectarray using VCC ($D_f(l)$).

grows which means the phase error in 2 GHz is becoming larger. From section II we know that the overlapping distance lp affects the reflection phase in lower frequency. As the coupling strength attenuates, the delayed phase diminishes. So we develop a variant-coupling-capacitance method in which we change the value of lp of each element according to its position to attain a more linear equivalent distance delay. Using this method the gain in lower frequency can be improved without deteriorating higher frequency performance. The method is explained in detail below.

Regarding the invariant-coupling-capacitance TCDRA, the space between neighboring elements is invariant. So s_i , the distance from $e_i(x_i, y_i)$ to the center, is

$$s_i = \text{sqrt}(x_i^2 + y_i^2) \quad (5)$$

In this paper, we aim to improve the linearity of $d_{2GHz}(l)$ to improve gain in 2 GHz. It is found that by decreasing lp the amount of delayed phase is decreased in lower frequency while stays mainly unchanged in higher frequency. Thus, we let coupling distance lp decreases as l increases. As a result, the delayed phase decreases and $d_{2GHz}(l)$ becomes closer to the designed line $d(l)$. The equation to calculate lp of elements of different positions is shown below.

$$lp_{\text{new}}(i) = -\frac{lp \cdot l(i) - l_{\text{max}} \cdot lp}{l_{\text{max}} - l_{\text{min}}} \quad (6)$$

In (6), $l(i)$ is the original TTD line length of e_i , l_{max} is the maximum value of l which is 28mm, and lp is the original coupling distance which is 1.5mm. We put the original value of $l(i)$ into this equation, and then the new coupling parameter $lp_{\text{new}}(i)$ of each element e_i is attained. The updated distance between e_i and its neighboring element nearer to the center is

$$\text{interval}(i) = \text{gap} + 2a - lp_{\text{new}}(i) \quad (7)$$

The y coordinate of e_i is unchanged. The x coordinate, x'_i and the distance from e_i to the center, $s'(i)$ are shown respectively

$$x'_i = \sum_{i=1}^n \text{interval}(i) \quad (8)$$

$$s'(i) = \text{sqrt}[(x'_i)^2 + y_i^2] \quad (9)$$

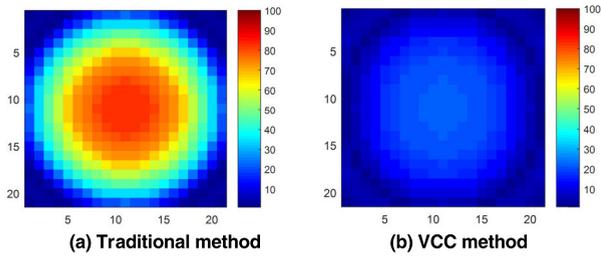


FIGURE 6. The phase error of the two reflectarrays in 2 GHz (unit: deg).

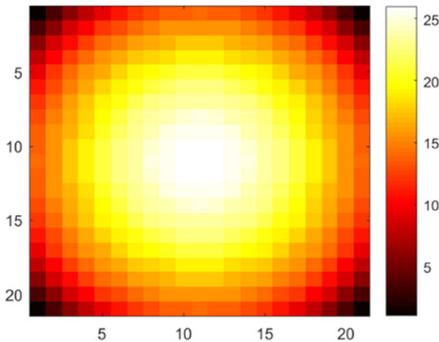


FIGURE 7. The length of phase delay line in the VCC reflectarray (unit: mm).

In (8), n is the number of elements between e_i and the center element which is in the same row with e_i . The updated equivalent distance delay for elements with variant coupling capacitance is shown in Fig. 5 in line with dots. Compared with the situation of fixed coupling capacitance, $D_{3GHz}(l)$, $D_{4GHz}(l)$, $D_{5GHz}(l)$, and $D(l)$ have little variation while $D_{2GHz}(l)$ becomes closer to our designed line $D(l)$ which means smaller phase error in 2 GHz but nearly invariable reflection phase in other frequencies. The phase error in 2 GHz before and after using VCC method is shown in Fig. 6. As can be seen, the phase error is reduced. Additionally, the phase delay line length of different elements in the VTCDRA is shown in Fig. 7.

IV. FEED ANTENNA AND REFLECTARRAY DESIGN

A. FEED ANTENNA

In this paper, a log-periodic dipole array (LPDA) is employed as the feed antenna. Though phase center of this antenna is not as stable as it of horn antenna, the flat structure causes less blockage and is easier fabricate. The LPDA is printed on a substrate (Rogers RO4350B) with the thickness of 0.8mm. The antenna is fed by a coaxial cable connected to the left end. The LPDA scaling factor is calculated in (10). The number of elements is 20. The parameters of the feed antenna is shown in table 1.

$$\tau = \frac{fl1}{fl2} = \frac{fw1}{fw2} \tag{10}$$

As the phase center of the feed antenna changes along with frequency, we take phase centers of six different frequency points sampled equidistantly from 2.5 GHz to 5 GHz and

TABLE 1. Parameters of the element and the feed antenna.

Parameter	Value (mm)
t_1	0.5
t_2	1
h_1	19.5
h_2	17.9
a	4
b	4.8
gap	1
x_l	1
l_p	1.5
d	6
d_y	16.4
w_l	1.9
f_{m1}	0.7
f_{l1}	44.3
f_{w1}	7.8
τ	0.85

TABLE 2. Coordinate of phase center.

Frequency/GHz	Phase Center Coordinate (x,y) /mm
2.5	(-58.9,0)
3	(-45.2,0)
3.5	(-36.3,0)
4	(-34.8,0)
4.5	(-25,0)
5	(-19.1,0)

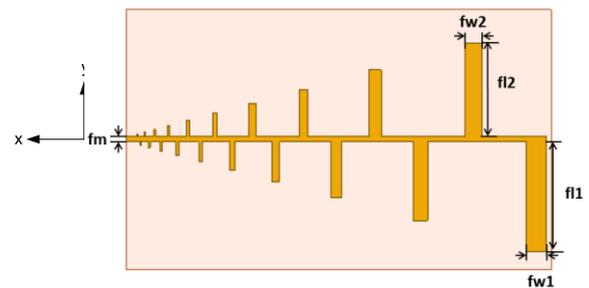


FIGURE 8. Feed antenna layout.

average the coordinate to obtain the equivalent phase center. The coordinate of phase center is shown in table 2. The layout of LPDA is shown in Fig. 8. Results in Fig. 9 show that the simulated and measured $|S_{11}|$ are both below -10 dB in the frequency range of 2 GHz to 5 GHz.

B. REFLECTING SURFACE

We design two reflecting surface using traditional method and VCC method respectively. Both TCDRA and VTCDRA are consist of 21×21 elements as shown in Fig. 10. From Fig. 10 (b) we can see that the VTCDRA has the shape of a lantern with marginally larger physical aperture area than

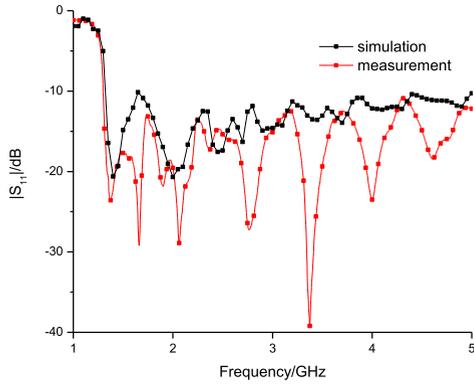
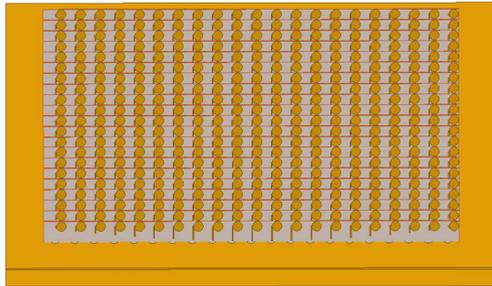
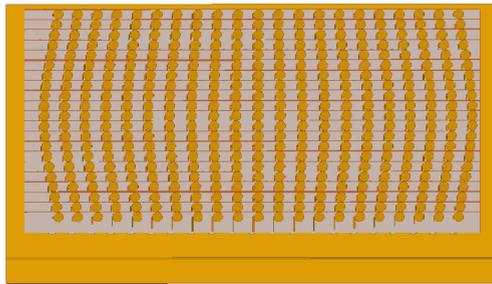


FIGURE 9. $|S_{11}|$ of the feed antenna.



(a) Invariant-coupling-capacitance reflecting surface



(b) Variant-coupling-capacitance reflecting surface

FIGURE 10. Layout of the reflecting surfaces.

the traditional TCDRA. We let F/D ratio equals 1. The side length of the reflectarray in Fig. 10 (a) is 350mm, so the distance between the equivalent phase center of feed antenna and reflecting surface is also 350mm. In order to control variables, the distance between the equivalent phase center of feed antenna and the reflecting surface of VTCDRA is kept the same. The physical aperture area of the VTCDRA is 120743mm^2 while the physical aperture area of the TCDDRA is 113360mm^2 .

V. SIMULATION AND EXPERIMENT VERIFICATIONS

The reflectarray element was simulated using floquet mode and the reflectarray radiation results were obtained using full wave EM simulation. The measurement of the radiation patterns was carried out using nearfield measurement shown in Fig. 11. Simulation and measurement results of radiation patterns in both E plane and H plane are shown in Fig. 12. Good agreement in radiation patterns is observed between the simulation and measurement results. The cross polarization

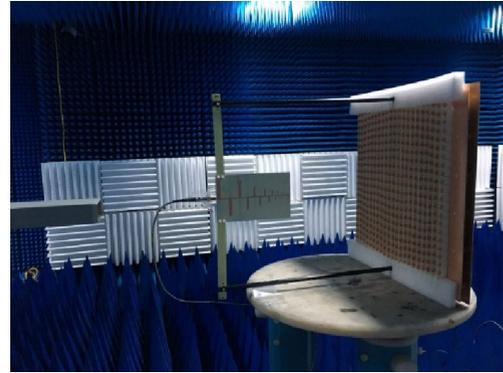


FIGURE 11. Nearfield measurement.

TABLE 3. Comparison of reflectarray antenna properties in references.

Ref.	Bandwidth	Maximum Aperture Efficiency	Method to achieve wide bandwidth
[5]	1.18:1	66%	Multi-resonance element
[9]	1.5:1	56.5%	Subwavelength element
[8]	1.45:1	64.7%	Spline element
[2]	1.5:1	not given	True-time-delay element
[13]	3.12:1	38%	Tightly coupled element & true-time-delay line
VTCDRA	2.5:1	47.5%	variant-coupling-capacitance method

discrimination is larger than 20 dB across the entire band which is smaller than simulation. This is because the installation is not perfectly accurate, resulting that feed antenna polarization is not strictly parallel with the reflectarray polarization. The measured antenna gain are given in Fig. 13. The VTCDRA gain varies from 14.4 dBi to 22 dBi. In 2 GHz, the gain is larger than the traditional TCDRA's by 3 dBi. Figure 13 also shows the measured aperture efficiencies of both TCDRA and VTCDRA. The VTCDRA aperture efficiency varies from 33.3% to 47.5%, peaking at 2.2 GHz. The aperture efficiency in the designed frequency, 2 GHz, is increased from 19.3% to 40.9%. The increment in other frequencies is due to the truncation effect in arrays. However, the increment in 2 GHz is 21.6% which is much higher than other frequency, which is able to demonstrate the effectiveness of the method. To state the good property of the proposed antenna, the performance of some recent wideband reflectarray antennas reported in the literature and the VTCDRA in this paper are summarized in table 3.

VI. CONCLUSION

In this paper, a tightly coupled dipole reflectarray antenna is presented. A variant-coupling-capacitance method is also

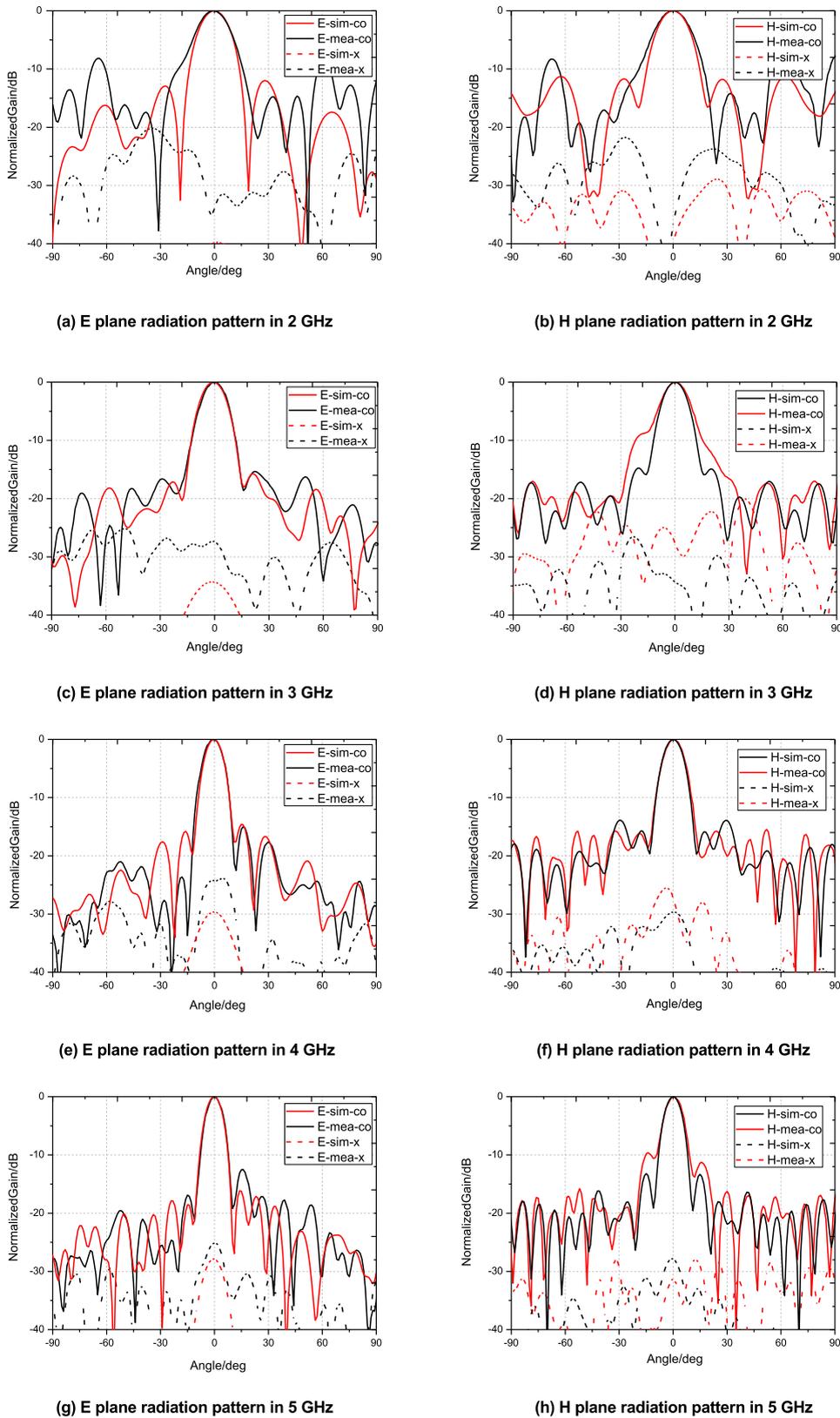


FIGURE 12. Radiation patterns of the VTCdra.

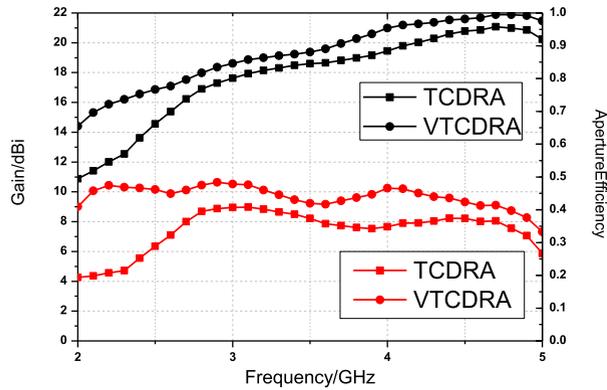


FIGURE 13. Measured gain and aperture efficiency of TCDRA and VTCDRA respectively.

proposed to improve the designed tightly coupled dipole reflectarray antenna gain in lower frequency by changing the coupling capacitance between elements according to their different positions in the reflecting surface. The traditional reflectarray and the modified reflectarray using variant-coupling-capacitance method are both studied and measured to verify the theory respectively. The two reflectarrays can both work from 2 GHz to 5 GHz. But the modified antenna gain is improved by 3 dB in 2 GHz with corresponding aperture efficiency increased by 21.6%.

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