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Dual-Beam Array Antenna Based on Circular Patch Elements with Conical Beam Pattern

Lan Cui, Shi-Shan Qi, Wen Wu*, and Da-Gang Fang

Abstract—A dual-beam microstrip array antenna based on conical beam elements is proposed in this paper. Circular patch operating at the TM_{01} mode is used to achieve conical beam pattern. Grating lobes of the array is used to obtain dual-beam patterns with large elevation angle and high gain. Detailed analysis and design have been presented. A 4×4 antenna prototype has been fabricated and measured. Experimental results show that the antenna array has the return loss better than 10 dB over 12.26 GHz–12.88 GHz and exhibits two symmetric radiation beams, directed at $\pm 49.4°$ with 16.6 dBi gain at 12.5 GHz. Good agreement between the simulated and measured results is observed. Compared with the previous scheme, the alternative proposal possesses the advantages of being easy to form a planar array with low cross-polarization and having relatively high aperture efficiency simultaneously.

1. INTRODUCTION

Nowadays, with the rapid development of wireless communications and radar systems, dual/multi-beam antennas are in great demand. For example, dual/multi-beam antennas are useful for indoor wireless systems which require multiple-coverage [1–3]. They reduce the required number of antennas and also improve the link quality, resulting in easier network deployment. Furthermore, a dual-beam along-track interferometric SAR (Synthetic Aperture Radar) has been developed for aircraft radar applications [4]. This new radar concept has led to the development of a new antenna configuration that allows a single antenna array to simultaneously generate two off-broadside squinted beams.

Microstrip antennas have been widely used because of its robustness, planar profile, and low cost [5–7]. Rectangular microstrip antenna operating at TM_{02} mode can radiate dual symmetric radiation beams, with each beam directed at $\pm 45°$ respectively [8, 9]. However, the beam-pointing angle of this kind of microstrip antenna is only fixed at $\pm 45°$. In [10], a dual-beam U-slot microstrip antenna has been proposed. But the two beams are not of equal levels and show a gain difference of 1.98 dB. Difference-beam patterns are always obtained by using two sub-arrays excited out of phase. It is noted that the beam-pointing angle is getting smaller with the increment of the array aperture [11–13]. Recently, the dual-beam steering microstrip leaky-wave antenna (MLWA) has been widely studied [14–16]. The dual-beam pattern with high efficiency can be easily implemented by MLWA without complicated feed networks. However, due to the characteristics of the leaky-wave antenna, the constant phase front will tilt from the antenna aperture along with the increment of the beam-pointing angle. Consequently, aperture efficiency of the MLWA becomes low for large beam-pointing angle. On the other hand, an antenna array having its neighboring elements excited with opposite phases and using grating lobes has been designed to generate the two off-broadside pointed beams [4]. In order to achieve low cross-polarization, the two rows of the array are excited with opposite feed locations and opposite phases, leading to the complicated feed network and the narrower bandwidth. However, if conventional feed

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* Corresponding author: Wen Wu (wuwen@mail.njust.edu.cn).
The authors are with the Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing 210094, China.

technique is used, the array shows a high cross-pol radiation of -13 dB when the beam is squinted to $30°$ [17].

Following the innovative idea proposed in [4], in this paper a dual-beam planar array using grating lobes based on the circular patch element with conical beam pattern is proposed. By properly choosing the element spacings d_x and d_y in the array based on the array theory, the desired beam-pointing angle and required side lobe levels (SLL) can be easily obtained. The feed network of the proposed dual-beam array antenna is simple because all the elements are fed in phase. This new design possesses the advantages of being easy to form a planar array with low cross-polarization and having relatively high aperture efficiency simultaneously for large beam-pointing angle. The design concept has been validated with the simulated and experimental results. A 4×4 dual-beam planar array with both large beam-pointing angle of $\pm 49.4°$ and gain of 16.6 dBi at 12.5 GHz has been developed.

2. ANALYSIS AND DESIGN

2.1. Array Analysis

For general planar array if M elements are placed along the x-direction and N elements placed along the y-direction as shown in Fig. 1, the array factor (AF) for the planar array can be written as [18]

$$AF = S_{xm} S_{yn} \tag{1}$$

where

$$S_{xm} = \sum_{m=1}^{M} I_{m1} e^{j(m-1)(kd_x \sin\theta \cos\phi + \beta_x)} \tag{2}$$

$$S_{yn} = \sum_{n=1}^{N} I_{1n} e^{j(n-1)(kd_y \sin\theta \cos\phi + \beta_y)}. \tag{3}$$

It is indicated that the pattern of a rectangular array is the product of the array factors of the arrays in the x- and y-directions respectively. Through exciting all the elements uniformly ($I_{m1} = I_{1n} = I_0$) and in phase ($\beta_x = \beta_y = 0$), the array factor is only determined by the element spacings along x- and y-directions.

In order to achieve a dual-beam pattern with maximum gain in x-direction based on conical beam antenna elements, element spacing d_x should be chosen to obtain the grating lobes at the elevation angle of the conical beam pattern. Location of grating lobe can be given by

$$\theta_0 = \arcsin\left(\frac{n\lambda_0}{d_x}\right) \tag{4}$$

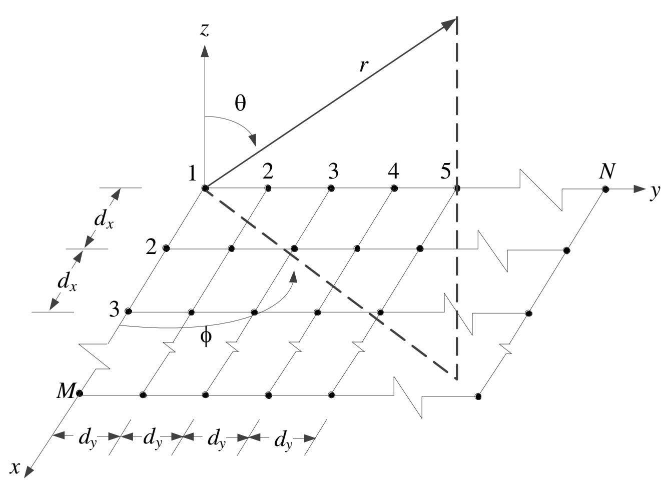


Figure 1. Planar array geometries.

where $n = \pm 1, \pm 2, \pm 3$, etc..

As an example, the array radiation pattern of a 4×4 planar array at 0° azimuth ($\phi = 0°$, x-z plane) is shown in Fig. 2, where the y-direction element spacing d_y is fixed at $0.75\lambda_0$. It is seen that with different element spacing d_x, the locations of grating lobes move. It is noted that when d_x is more than $2\lambda_0$ (e.g., $d_x = 2.4\lambda_0$), the grating lobes appear at $\pm 25°$ and $\pm 56°$. The second set of grating lobes appear. In this case, a large array is more appropriate than a small one. It is because that the beamwidth of a large array is narrower and the second grating lobes can be better canceled by the product of the array factor and the element pattern. Thus, for dual-beam array with small beam-pointing angle, large array is proposed for application. In our proposed design elevation angle of conical beam element is at $\pm 50°$, so n should be ± 1 and the element spacing d_x should be $1.3\lambda_0$. There is only one set of grating lobes. Since the element radiates conical beam with a null at the broadside, the broadside beam of the array can be eliminated by the multiplication of the element pattern and the array factor. It is noted that element spacing d_y should be less than one wavelength and chosen properly to achieve broadside beam cancelation in the y-direction. The array radiation patterns with different element space d_y at 90° azimuth ($\phi = 90°$, y-z plane) are presented in Fig. 2(b), where d_x is fixed at $1.3\lambda_0$. It can be seen that there is only a broadside beam in the y-z plane which will disappear after multiplied with the conical radiation pattern of the antenna element. The beamwidth of the broadside beam, the side lobe locations and levels change along with the variation of the element spacing d_y. Amplitude tapering can also be employed to achieve lower SLL for requirement.

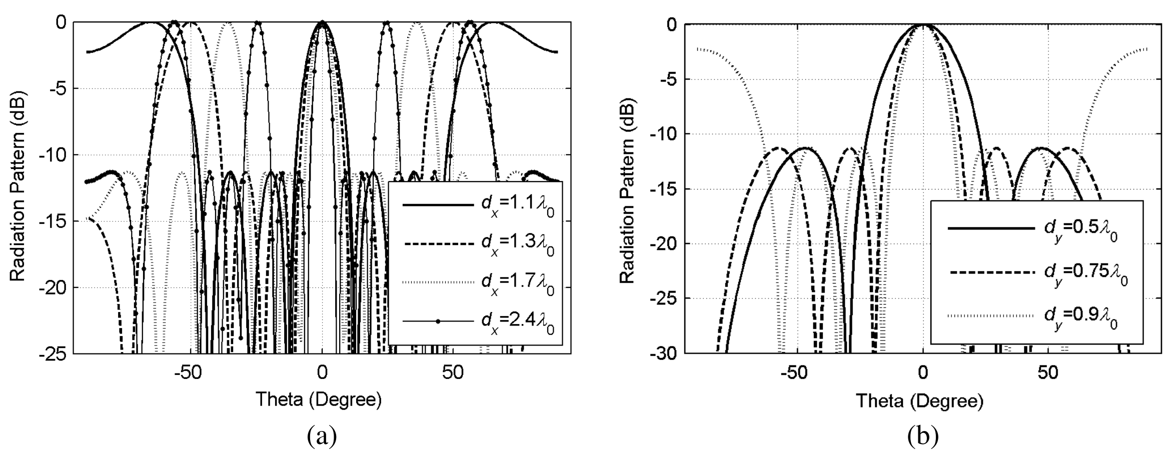


Figure 2. Radiation patterns of the planar array (a) in x-z plane and (b) in y-z plane.

2.2. Single Antenna Design

To demonstrate the performance of the proposed dual-beam array antenna, a circular patch antenna element with conical beam has been designed. Full wave simulator Ansoft HFSS has been used to design and to simulate the antenna. The substrate (Rogers 4003) with relative permittivity of 3.55 and thickness t of 1.5 mm is used for the array. TM_{01} mode of the circular patch fed by a coax-probe at the center has been employed to generate the conical beam radiation pattern. The operating frequency is 12.5 GHz. The configuration of the patch is presented in Fig. 3. The circular patch has a radius of $R_p = 6.57$ mm and a circular slot with a width of $s = 0.4$ mm ($R_c = 0.5$ mm).

Figure 4(a) shows the simulated and measured reflection coefficients of the antenna element. For $|S_{11}| < -10$ dB, the measured impedance bandwidth is 7.2% at 12.5 GHz. The simulated normalized radiation patterns are given in Figs. 4(b) and (c). The maximum simulated gain is 5.2 dBi at the beam-pointing angle of 50°. The pattern has almost no ripple variation in the azimuthal plane.

2.3. Array Experimental Results

A 4×4 dual-beam array antenna operating at 12.5 GHz has been fabricated and measured for the validation of the proposed design method. Considering the required beam-pointing angle of $\pm 50°$ in x-z plane and SLL requirement in y-z plane with elements in uniform amplitude, the distance between adjacent antenna elements is set to 31.2 mm ($1.3\lambda_0$) along the x-direction and 18 mm ($0.75\lambda_0$) along the y-direction, respectively. The fabricated array antenna is shown in Fig. 5. The parallel feed network (Fig. 5(b)) is printed on a microstrip substrate (Arlon 880) with the relative permittivity of 2.2 and thickness of 0.508 mm. 16 coaxial cables are used to connect the conical beam elements with the feed network.

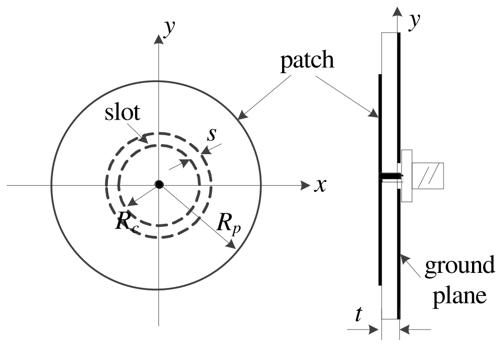


Figure 3. Configuration of the conical beam circular patch antenna.

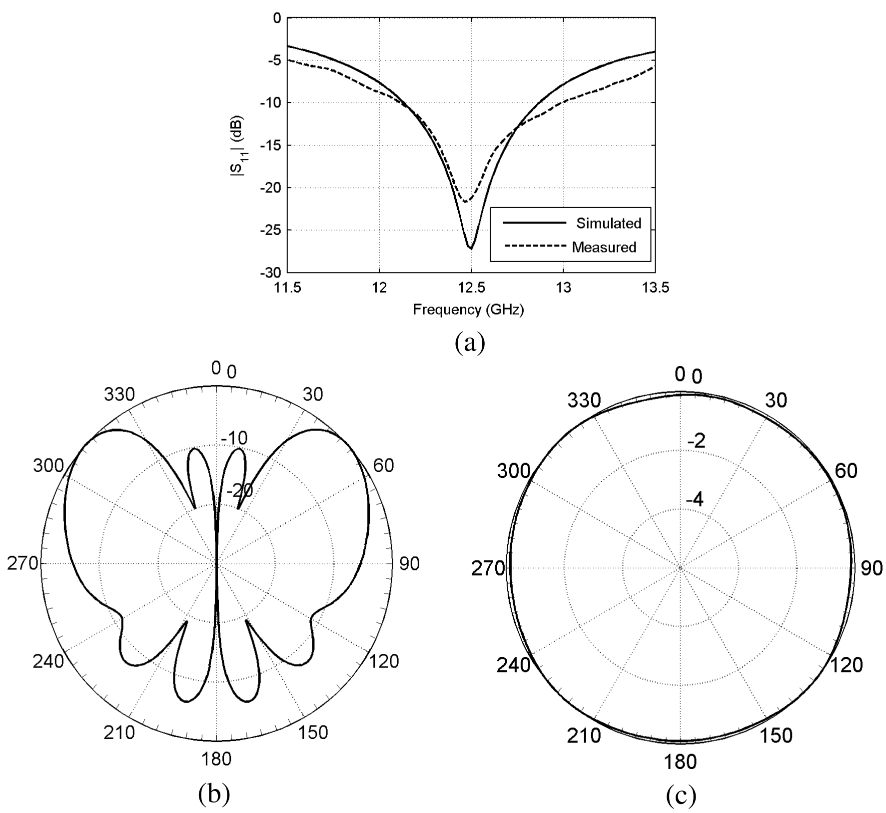
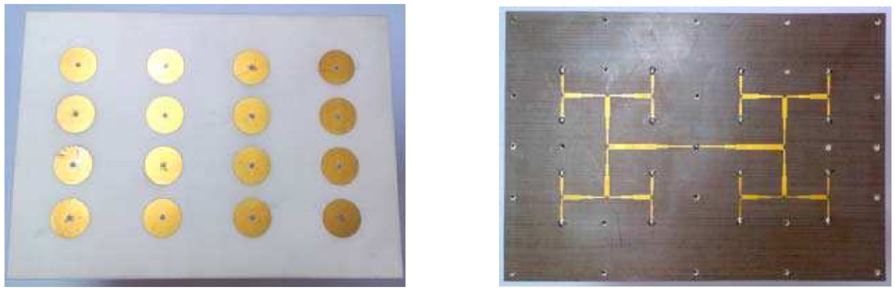


Figure 4. Reflection coefficients and radiation patterns of the conical beam element. (a) Simulated and measured results of $|S_{11}|$, (b) simulated normalized radiation patterns in the x-z plane and (c) in the x-y plane.



(a) (b)

Figure 5. Fabricated prototype of the proposed antenna. (a) 4×4 array elements, and (b) feed network.

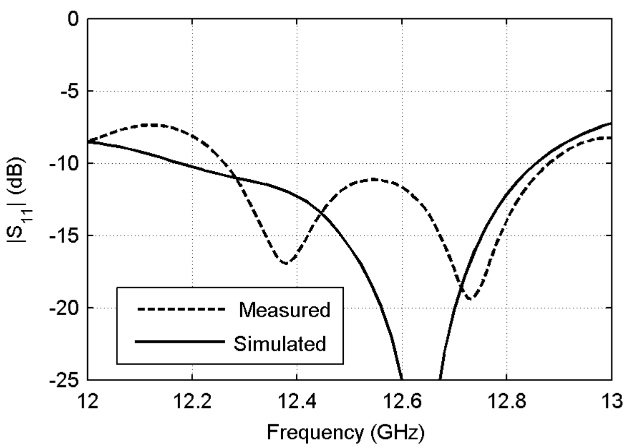


Figure 6. Measured and simulated reflection coefficients.

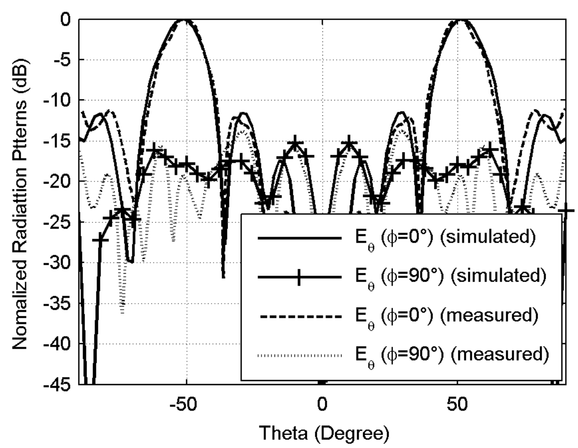


Figure 7. Measured and simulated radiation patterns.

Figure 6 presents the measured and simulated reflection coefficients of the entire array. The observed measured -10 dB impedance bandwidth is from 12.26 to 12.88 GHz. The ripples in the measured result are caused by the long coaxial cables. Fig. 7 shows the measured and simulated radiation patterns at 12.5 GHz. It is seen that the two beams are symmetrically located at $\pm 49.4°$, the 3-dB beamwidth of each beam is equal to $13.6°$ and the peak side lobe level is -11.5 dB. The measured antenna peak gain at 12.5 GHz is 16.6 dBi while the simulated one is 0.2 dB higher. The measured cross-pol level is -24 dB and the simulated level is -57 dB. The difference between the measured result and the simulated one is due to the background noise. The aperture efficiency is 42.9%, which is much higher than 27.8% of conventional microstrip dual-beam leaky wave antenna array [14].

3. DISCUSSION

As mentioned in the introduction, the beam-pointing angle of conventional difference-beam array antenna is becoming smaller with the increasing array aperture, while the beam-pointing angle using the proposed design concept will not change when larger array is applied. For validation of the proposed dual-beam array antenna design concept, another 8×8 uniform planar array has been designed. The full-wave simulated radiation patterns are shown in Fig. 8. It can be seen that the dual beams also radiate to $\pm 50°$ with 23.3 dBi gain around 6 dBi higher than that of the 4×4 array and the 3-dB beamwidth is $7.3°$. The beam-pointing angle is not shifted and high gain is still achieved. This simulation result indicates that the proposed scheme is suitable for the design of larger array with high gain.

Furthermore, in the fabricated 4×4 array, antenna elements are all excited in uniform amplitude

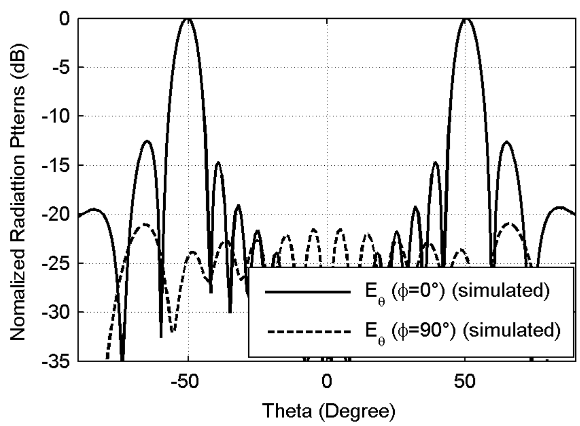


Figure 8. Simulated radiation patterns of an 8×8 dual-beam array antenna.

and in phase. A side lobe level of $-12\,\mathrm{dB}$ is obtained. If lower SLL is required, it is also very easy to realize using familiar amplitude distribution like Dolph-Chebyshev, Taylor, and etc.

In aspect of dual-beam antennas with smaller beam-pointing angle, the design concept still can be employed. However, in such a case the radius of a conventional circular patch with small beam-pointing angle is large, and the element spacing d_y ($< \lambda_0$) is too small to locate the elements. Consequently, compact elements are needed to solve the size problem in the design. A compact circular patch antenna for conical-pattern radiation was proposed in [19]. A broadband microstrip monopolar patch antenna was proposed in [20] with a patch radius of only $0.36\lambda_0$. These compact elements can be employed in the array design. In both applications the proposed design method for dual-beam array antenna is still applicable.

4. CONCLUSION

A dual-beam planar array antenna with large elevation angle has been proposed and investigated. In order to achieve gain enhancement with large beam-pointing angle and simplify the feed structure, grating lobes are employed in this array. The antenna is operating at 12.5 GHz. The beams are directed at $\pm 49.4^\circ$ with gain of 16.6 dBi. Good agreement between the measured and simulated results has validated the proposal. This proposed array antenna also shows lower cross-pol level than that in the dual-beam array using rectangular patch elements based on conventional feed technique. This design is a good candidate for communications and radar systems.

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