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A Dual-Band Shared Aperture Antenna Array in Ku/Ka-Bands for Beam Scanning Applications

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ABSTRACT A dual-band shared aperture antenna array for phased array system operated in Ku/Ka-bands is proposed in this paper. By judiciously designing the geometrical structure and parameters, compact and integrated antenna elements are proposed to achieve the maximum scanning angle without the grating lobes phenomenon. The patch-dipole antenna elements operating in Ku-band and microstrip patch antenna elements operating in Ka-band are designed and fabricated utilizing a four-layer lamination substrate. Metal shielding vias are introduced to suppress the coupling between the antenna elements operating in different bands, meanwhile, defected ground structure is introduced to eliminate the scan blindness effect and improve the beam scanning range effectively. The proposed antenna array has 208 Ku-band elements and 832 Ka-band elements distributed in the shared aperture with a diameter of 200 mm. Measured results show that the proposed antenna array has a broad impedance bandwidth of 10.7% in Ku-band and 9.1% in Ka-band, meanwhile it has a relatively wide scanning angle ranging from −45° to +45° with low gain decrease and side lobe level. The proposed phased array antenna has potential application in a radar system, mobile communication system, and so on.

INDEX TERMS Phased array antenna, dual band, shared aperture.

I. INTRODUCTION

In the past few decades, phased array antenna has obtained a great development [1]–[3]. The beam scanning performance of phased array antenna is realized by controlling the feeding phase of each antenna unit cell electronically [4], [5], which can overcome the heavy servomechanism structures of the traditional mechanical scanning antenna. Benefit from the performances of fast scanning speed and flexible beam controllability [6], [7], phased array antenna has been widely applied in mobile communication [8]–[11], satellite navigation systems [12]–[14], radio astronomy [15]–[17] and radar systems [18]–[20].

Generally, each element of the phased array antenna has a transmitting and a receiving channel, which makes it can be used to search, identify and track target simultaneously [21], [22]. To realize multiple targets searching and tracking, multi-band shared aperture phased antenna array is proposed [23]–[25]. The shared aperture phased antenna array, which means antennas operating in different frequency bands share a common aperture with reduced weight and size [26], makes it suitable for mobile platform applications [27]. Several approaches have been proposed to achieve dual-band dual-polarized shared aperture antenna array. A dual-band dual-polarized planar array operating in L-band and X-bands were presented in [26]. A series of dual-band or tri-band shared aperture antenna arrays with dual polarizations for digital beamforming synthetic aperture radar (DBF-SAR) system have been reported in [28]–[30]. In addition, the method of interlacing the antenna elements in different bands has been widely applied for radar system [31], [32]. Several dual-band shared aperture antenna array for phased array have been reported recently [33]–[37]. However the antenna array which operates in two well-separated band with a wide beam scanning capability is still required for radar system.

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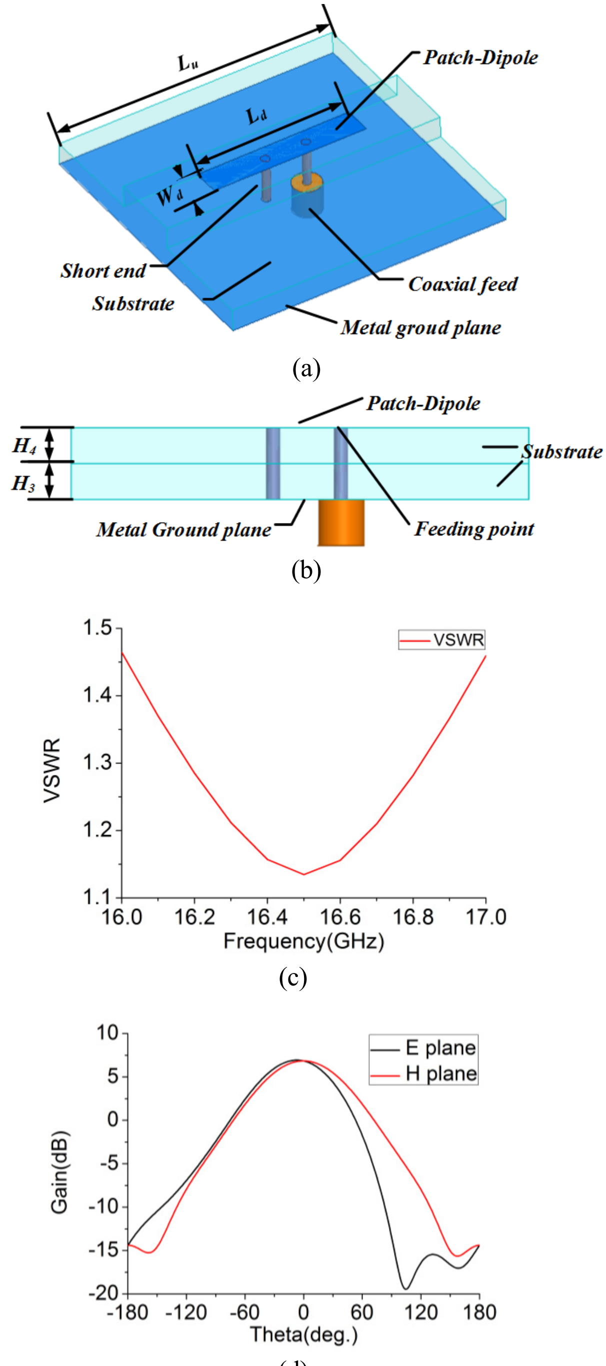
To achieve the required beam scanning performance, leaky wave antenna array [38]–[40], composite right/left handed microstrip leaky-wave antenna [41]–[44], and the continuous transverse stub array [45], [46] have been proposed and verified in microwave and millimeter-wave band. For phased array system, the beam scanning performance is realized by introducing phase shifter to each antenna element. But the performances, such as the scanning range, the gain and the side lobe degradation, are achieved by antenna array design. In this paper, a dual-band shared-aperture phased antenna array is proposed to work in Ku/Ka-bands with a diameter of 200 mm. By judiciously designing geometrical structure and parameters, compact and integrated unit cells are proposed to achieve the maximum scanning angle without the grating lobes phenomenon. For the proposed antenna elements, metal shielding vias are introduced to suppress the coupling between the antenna elements operating in different bands, meanwhile defected ground structure (DGS) is introduced to eliminate the scan blindness effect and improve the performance of antenna array in beam scanning range effectively. The proposed antenna array is measured by integrated with the phased array system to verify its two-dimensional beam scanning ability. The measured results show that for our proposed phased antenna array, the maximum scanning angle can reach 45° in both operating bands. To optimize the performances of the phase antenna array, several factors, such as the geometry of the unit cells, the feeding technique and the coupling between the unit cells are discussed in detail in this paper.

II. DESIGN OF THE ANTENNA ELEMENTS

A patch-dipole antenna operating in Ku-band is designed as shown in Fig. 1a and 1b. It is composed of patch dipole, short end and the sheet reflector [47], [48]. The proposed Ku-band antenna element is fabricated utilizing a TSM-DS3 substrate. The permittivity of substrate ε_r is 2.95, and the total thickness H_u is 1.524 mm. A metal grounding via is introduced to connect the patch-dipole and the ground plan plane, and the antenna is fed by a coaxial cable. For the patch dipole structure, the length is 5.1 mm, and the width is 1mm. The VSWR and gain patterns of proposed patch-dipole antenna simulated by ANSOFT HFSS are shown in Fig. 1c and 1d. The maximal gain can reach 6.8dB. The 3dB beam width is 90° in E-plane and 82° in H-plane respectively. For the proposed antenna structure, stepped type substrate is used to reduce the interaction effect between the Ka-band and Ku-band antenna elements.

To improve the performance of miniaturization and integration, a microstrip patch antenna with slot coupling feeding structure is proposed to operate in Ka-band. As shown in Fig. 2a and 2b, the Ka-band antenna element is also fabricated using three-layers TSM-DS3 substrate with the thickness of H_1, H_2, and H_3 respectively ($H_1 = 0.508$mm, $H_2 = 0.254$mm, $H_3 = 0.762$mm). The I-shaped slot is introduced here to achieve the broad bandwidth performance. The metal shielding vias, which connect the metal ground layer and coupling slot layer, are utilized to increase the isolation between the Ka-band antenna elements. Here, the value of the parameters is set as $L_p = 1.9$ mm, $W_p = 1.8$ mm, $W_s = 0.4$ mm and $L_a = 5$ mm. Fig. 2c and 2d show the simulated VSWR and gain patterns of the proposed Ka-band antenna element. The maximal gain is simulated to be 5.6dB, and the 3dB beam width in E-plane and H-plane are 93° and 113° respectively.



(a)

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FIGURE 1. The proposed Ku-band antenna element. (a) Struture of the patch-dipole antenna, (b) side view of the patch-dipole antenna, (c) simulated VSWR and (d) gain of the proposed Ku-band antenna element.

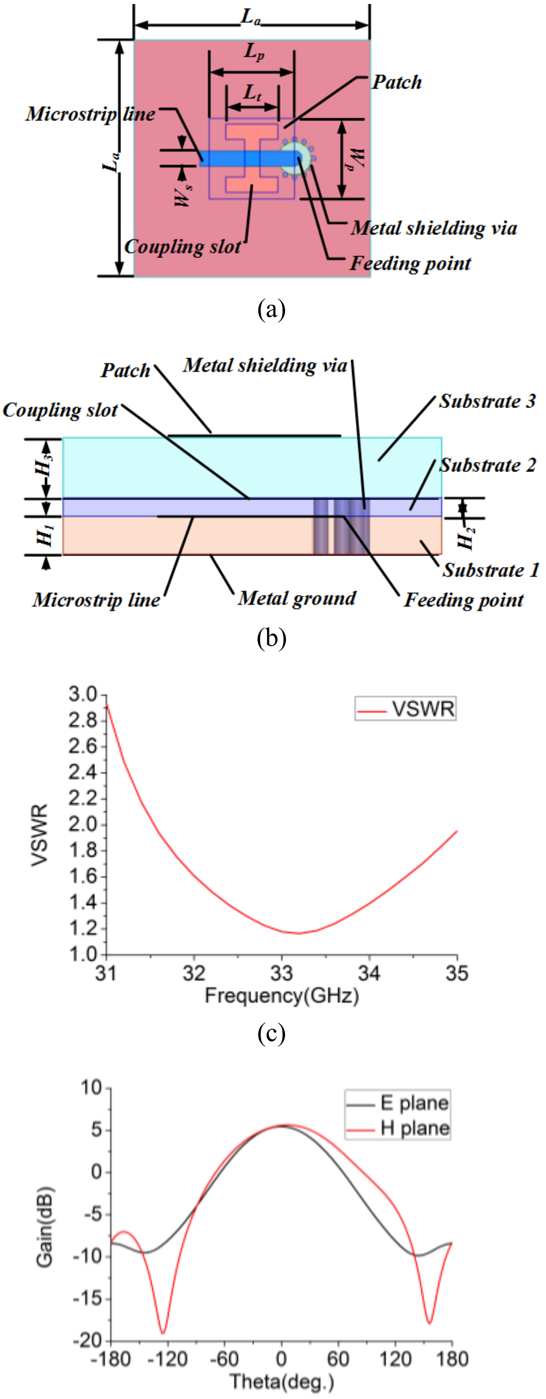

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FIGURE 2. **The proposed Ka-band antenna element. (a) Struture of the microstrip patch antenna, (b) side view of the microstrip patch antenna, (c) simulated VSWR and (d) gain of the proposed Ka-band antenna element.**

For a dual-band phased array antenna, the integration of the antenna elements becomes more and more important since the available space for the antenna array in radar system is limited. For our design, the proposed elements are arranged in a rectangular array. To make sure the phased array antenna has the maximum scanning angle without the grating lobes phenomenon, the required element spacing d can be calculated by using (1) [1]:

$$d \leq \frac{\lambda_{\min}}{1 + |\sin\theta|} \tag{1}$$

where $\lambda_{\min}$ is the minimum wavelength in the operating band, θ is the desired scanning angle, which is 45° for our proposed dual-band phased array antenna. The maximum element spacing is calculated to be 10.33 mm in Ku-band and 5.17 mm in Ka-band respectively. Therefore, the proposed dual-band antenna array is arranged with the element spacing of $L_u = 10$mm for Ku-band elements and $L_a = 5$mm for Ka-band elements, which means the antenna element has a miniaturized size of 0.55λ in both Ku- and Ka-band. The super-cell structure of the proposed dual-band shared-aperture antenna array, which is composed of one Ku-band element and four Ka-band elements, is shown in Fig. 3a and 3b. Four layers substrate is utilized for our design ($H_1 = 0.508$mm, $H_2 = 0.254$mm, $H_3 = 0.762$mm, $H_4 = 0.762$mm). Here, the metal ground plane for the proposed Ku-band antenna element and the coupling slot layer for the proposed Ka-band antenna element are set to be the same, which means $Hu = H_3 + H_4 = 1.524$mm. The feeding positions are determined by the interface of T/R module. Fig. 3c shows the stack-up configuration of the proposed super cell. Via #1 and via #2 are connected to the Ku- and Ka-band coaxial feed respectively. Via #3 works as the metal shielding via, and via #4 works as the short end of the Ku-band dipole. Although via #2, #3, #4 are blind holes, via #3, #4 do not need to be connected to any other RF connectors, which means they can be fabricated easily.

For our design, the maximum scanning angle and the scan blindness effect can be affected by the mutual coupling between the antenna elements operating in different bands and the surface wave supported by antenna structure [49]–[52]. To eliminate this, metal shielding vias and DGS are introduced in our design, which can truncate surface waves and suppress the mutual coupling, as shown in Fig. 3. The energy is bound to the antenna structure as the surface wave when the scan blindness effect happens. The DGS is a kind of brackets-shaped slot, which can interdict the surface wave. Therefore, the ratio of the transmitted power P_o to the input power P_{in} is utilized to evaluate the improvement of the antenna performance in Ka band by introducing DGS to the ground layer, which can be calculated by using (2) [1]:

$$\frac{P_0}{P_{in}} = 1 - |\Gamma|^2 \tag{2}$$

where Γ is the antenna active reflection coefficient. The simulated results are shown in Fig. 4, from which we can see that the scan blindness effect can be suppressed effectively in Ka-band.

III. THE ANALYSIS OF ANTENNA ARRAY

The schematic diagram of the complete antenna array is shown in Fig. 5a, which has 208 Ku-band elements and

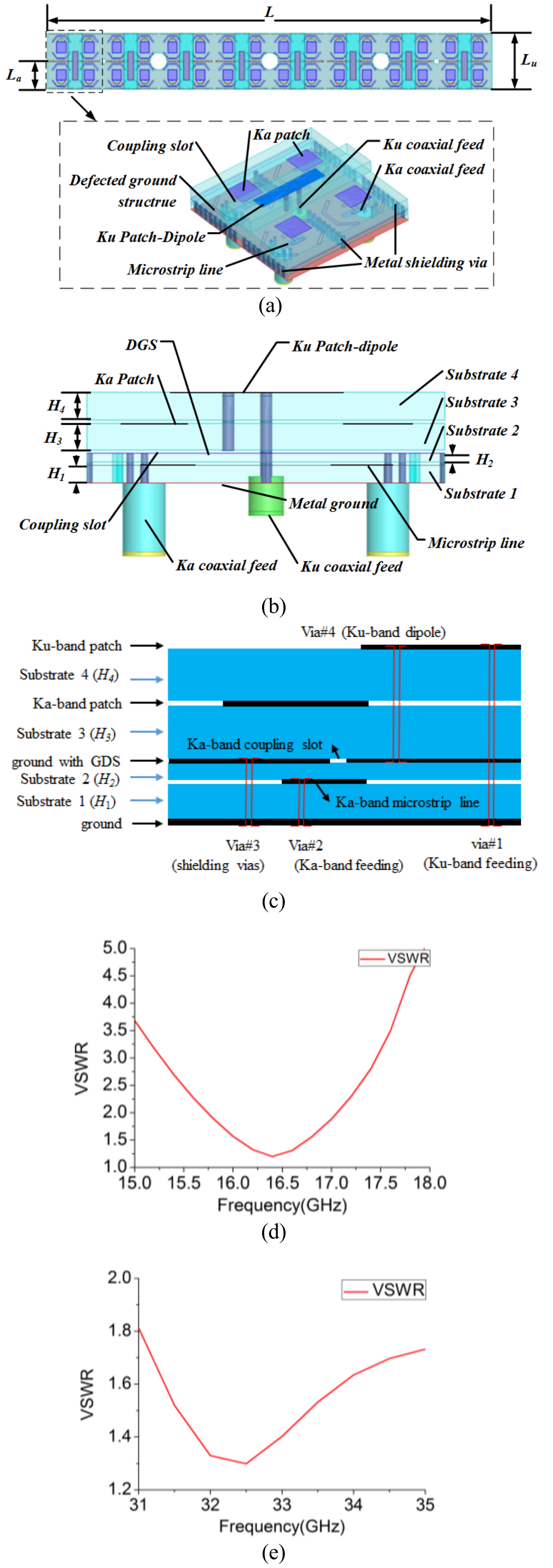


FIGURE 3. The proposed dual-band antenna element. (a) The super-cell structure of the proposed dual-band shared-aperture antenna array, (b) side view. (c) Configuration and stack-up of super cell. (d) The simulated VSWR in Ku-band, and (e) the simulated VSWR in Ka-band.

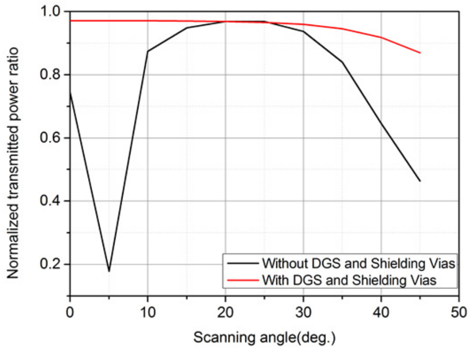
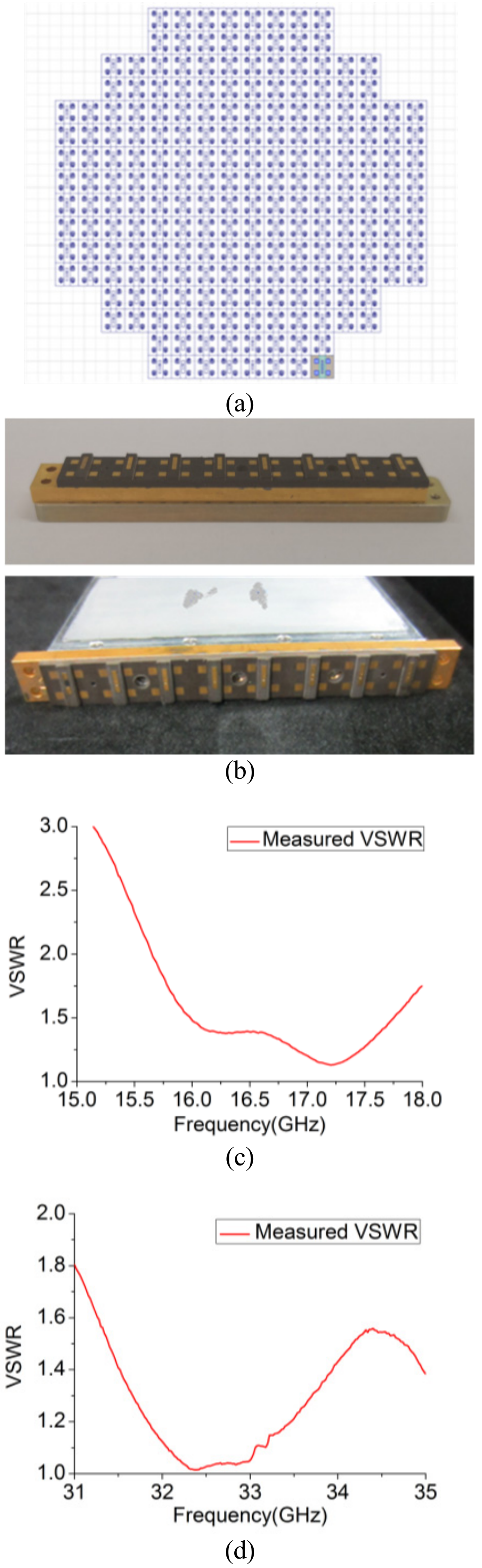


FIGURE 4. The normalized simulated transmitted power ratio.

832 Ka-band elements in total, and these elements are distributed in the aperture with a diameter of 210 mm. The maximal number of the super-cells along x- or y-axis is 16. Fig. 5b gives the fabricated antenna structure contains 8 super-cells integrated with the T/R modules. It is composed of 8 Ku-band antenna elements and 32 Ka-band antenna elements, with the total size of 10mm × 80mm. In order to integrate all the antenna elements to the phased array system, advanced multilayer substrate processing technology and tiny electrical connector technology have been adopted in our fabrication. The utilized tiny electrical connector, which has a diameter of 1.4 mm, makes it possible to connect the antenna elements to the T/R modules. The measured results of the VSWR for the proposed antenna array are shown in Fig. 5c and 5d. The measured impedance bandwidth ranges from 15.9 GHz to 17.7 GHz in Ku-band, and from 31.4 GHz to 34.4 GHz in Ka-band, in which the VSWR keeps below 1.6. We can calculate that the relative bandwidth is 10.7% in Ku-band, and 9.1% in Ka-band. The proposed antenna array has broad bandwidth in each operational band.

The normalized radiation patterns are simulated and shown in Fig. 6. Here we focus on the performance of the scanning range, the gain and the side lobe degradation of the proposed antenna array. Since for radar detection system, a wide scanning angle means a larger detection range, and the high gain performance of the antenna array can increase the detection distance with the same transmitted power. Meanwhile the side lobe level of antenna array directly affects the anti-interference capability of radar system. It can be seen that in both E- and H-plane, the 3dB beam width of the antenna array is 6° in Ku-band. The scanning angle can range from −45° to +45° with a step of 15° using our phased array system. At the maximal scanning angle of 45° in the E-plane, the gain decreases 2.6 dB, meanwhile the side lobe degradation is 2.2dB. While in the H-plane, the gain decreases 2.2dB and the side lobe degradation is 2.0 dB when the scanning angle reaches 45°. In Ka-band, the normalized radiation patterns are simulated and shown in Fig. 6c and 6d. The 3 dB beam width is 3° in both E-plane and H-plane. In the E-plane,



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(b)

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FIGURE 5. (a) Schematic diagram of the proposed shared-aperture antenna array, (b) fabricated antenna elements integrated with the T/R modules, (c) measured VSWR of the antenna array in Ku-band, and (d) measured VSWR of the antenna array in Ka-band.

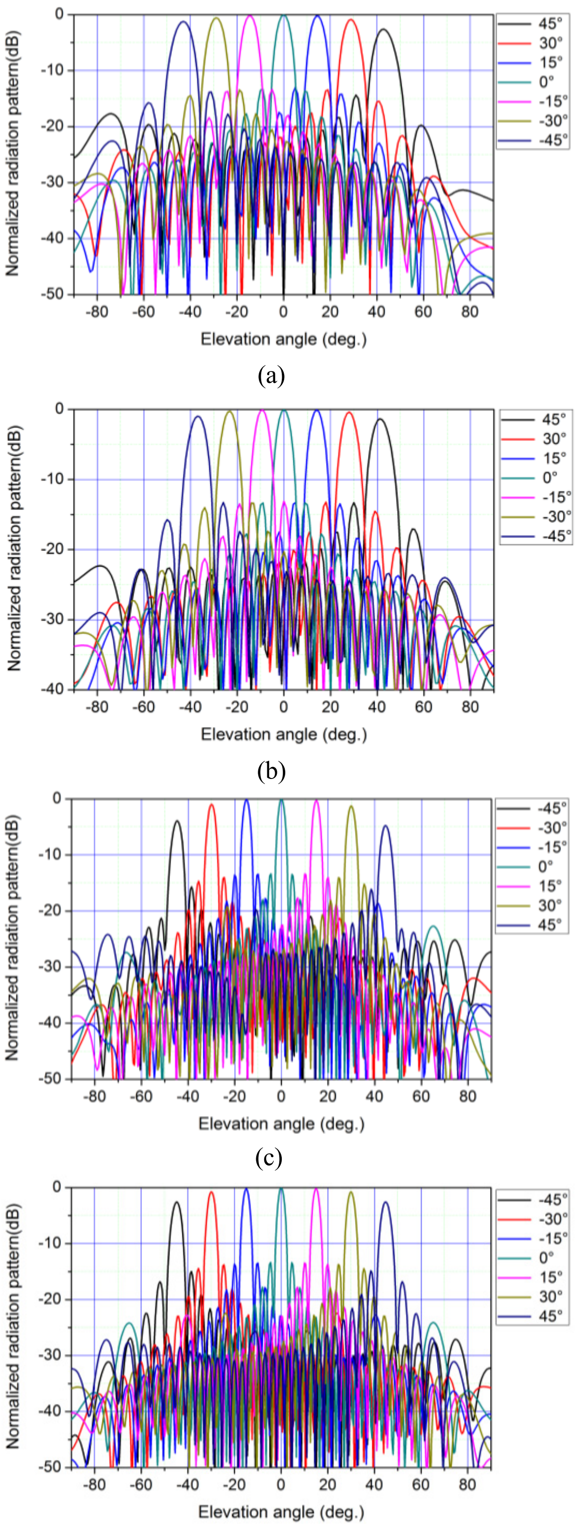

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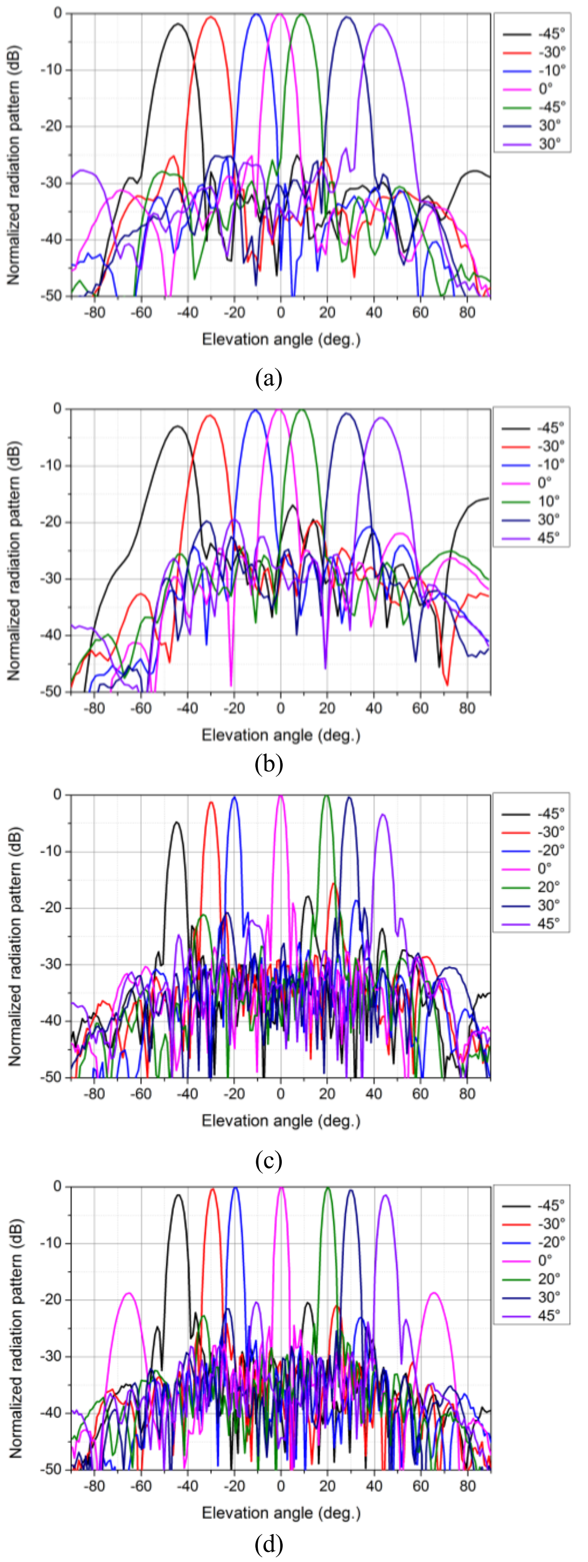
FIGURE 6. (a) Normalized simulated radiation patterns in E-plane operating in Ku-band, (b) normalized simulated radiation patterns in H-plane operating in Ku-band, (c) normalized simulated radiation patterns in E-plane operating in Ka-band, and (d) normalized simulated radiation patterns in H-plane operating in Ka-band.



(a)

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FIGURE 7. **(a) Normalized measured radiation patterns in E-plane operating in Ku-band, (b) normalized measured radiation patterns in H-plane operating in Ku-band, (c) normalized measured radiation patterns in E-plane operating in Ka-band, and (d) normalized measured radiation patterns in H-plane operating in Ka-band.**

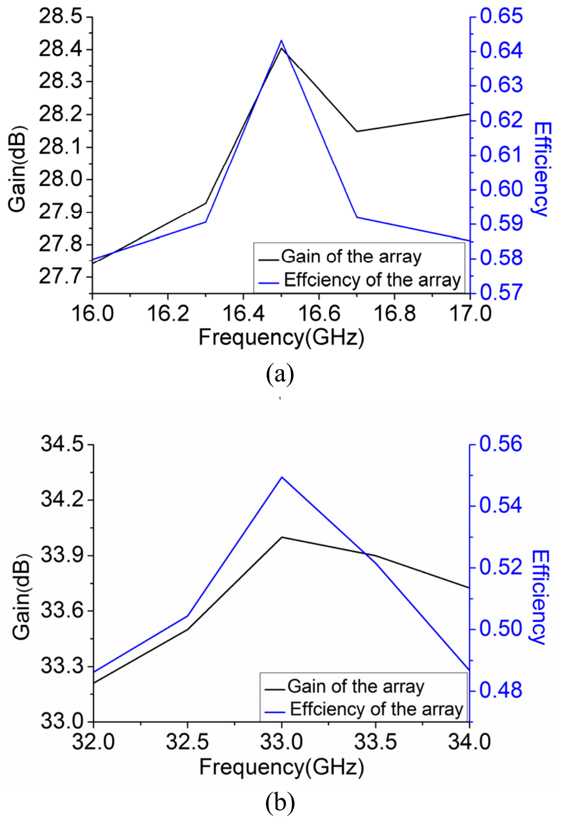

FIGURE 8. **Measured passive gain and efficiency of the proposed antenna array in (a) Ku-band and (b) Ka-band.**

the gain decreases 4.7 dB, and the side lobe degradation is 2.2 dB when the scanning angle reaches 45°. Meanwhile in the H-plane, the gain decreases 2.3 dB and the side lobe degradation is 1.2 dB at the maximal scanning angle.

To achieve the low side lobe level performance, Taylor weighted distribution of feeding amplitude is utilized for the proposed phased array antenna operated in Ku-band. Fig. 7a and 7b show the measured radiation patterns in E-plane and H-plane when the scanning angle is ±45°, ±30°, ±10° and 0° respectively. In the E-plane, the 3 dB beam width is 6.4°, which agrees very well with the simulated results. The measured gain is 28.4 dB and the side lobe level is −24.5 dB when the scanning angle is 0°. At the maximum scanning angle of 45°, the measured gain changes to be 25.4 dB, and the side lobe level is −21.5 dB. It can be calculated that the gain decreases 3 dB, and the side lobe degradation is 3 dB when the radiation angle is 45°. While in H-plane, the 3 dB beam width is also 6.4°, and the side lobe level is −25 dB when the scanning angle is 0°. At the maximum scanning angle of 45°, the gain decreases 1.8 dB, meanwhile the side lobe degradation is 2.7 dB.

When the proposed phased array antenna works in Ka-band, the normalized radiation patterns are measured as shown in Fig. 7c and 7d. The measured results show that the

TABLE 1. Comparison with other dual band phased arrays.

Item	Our work	K/Ka-bands array[33]	X/Ku-bands array[34]	L/S-bands array[35]	K/Ka-bands array[36]	L/S-bands array[37]
Bandwidth	10.7% in Ku-band 9.1% in Ka-band (VSWR≤1.6)	8.1% in K-band 5.5% in Ka-band	3.1% in X-band 7% in Ku-band	2.8% in L-band 6.6% in S-band	5.0% in K-band 2.0% in Ka-band	2.2% in L-band 3.4% in S-band
Dual band frequency ratio	2:1	1.5:1	1.8:1	2:1	1.5:1	2.2:1
Scanning range	±45°	±60°	±50°	±50°	±60°	±60°
Gain decrease	3dB in Ku-band 4.5dB in Ka-band	7.5dB in K-band 8dB in Ka-band	5dB in X-band 5dB in Ku-band	5dB in L-band 5dB in S-band	5dB in K-band 6dB in Ka-band	4dB in L-band 4dB in S-band
Side-lobe level	-21.2dB	-8dB	-14dB	-5dB	-10dB	-10dB

3 dB beam width is 3.2° and the measured gain is 34.0 dB and the side lobe level is −25dB in E-plane when the scanning angle is 0°. The maximum scanning angle of 45°, the measured gain changes to be 29.5 dB, and the side lobe level is −22 dB. It can be calculated that the gain decreases 4.5 dB, and the side lobe degradation is 3 dB when the radiation angle is 45°. In H-plane, the 3 dB beam width is 3.2° and the side lobe level is −25 dB when the scanning angle is 0°. When the scanning angle reaches 45°, the gain decreases 1.3 dB, meanwhile the side lobe degradation is 3.8 dB. The simulated and measured results in Ku-and Ka-band agree very well as shown Fig. 6 and Fig. 7, verifying the scan blindness effect can be suppressed effectively in Ka-band.

Fig. 8a and 8b show the measured passive gain and efficiency of the Ku-band array and Ka-band array. The scanning bandwidth, in which the beam scanning performance of the antenna array meets our requirement, ranges from 16GHz to 17GHz in Ku-band, and from 32GHz to 34GHz in Ka-band. We can see that the scanning bandwidth is contained in the measured impedance bandwidth, which means the VSWR keeps below 1.6 in the scanning bandwidth. The measured results show that the efficiency in Ku-band array keeps above 58%, and in Ka-band it keeps above 48.7%.

Compared with other published dual-band phased arrays antenna [33]–[37], the proposed antenna array has a low profile and a low lost, and can be easily integrated with the phased array system. By judiciously designing geometrical structure and parameters, miniaturized and integrated unit cells are proposed to achieve the maximum scanning angle without the grating lobes phenomenon. Metal shielding vias are introduced to suppress the coupling between the antenna elements operating in different bands, meanwhile DGS is introduced to eliminate the scan blindness effect and improve the performance beam scanning effectively. The proposed antenna array also supports a larger operational frequency ratio of 2:1, as shown in Table I. In each operational band, the proposed antenna array has broad bandwidth. The proposed antenna array enables great wide-angle scanning ability with less gain decrease, and the side lobe level can keeps below −21.2dB in the whole scanning range.

IV. CONCLUSION

In conclusion, our proposed antenna array shows the advantage of both detection range and sensitivity, which is significant for radar system and mobile communication system. An antenna array operated in Ku- and Ka-band is proposed, simulated, fabricated and measured in this paper. The simulated and measured results agree very well, and it is verified the proposed antenna array has a broad impedance bandwidth of 10.7% in Ku-band and 9.1% in Ka-band, in which the VSWR keeps below 1.6. The beam scanning range can cover the whole range from −45° to +45°, in which the gain decreases keep less than 3dB for Ku-band and 4.5dB for Ka-band. The proposed phased array antenna has potential application in radar system, mobile communication system and so on. It also establishes the foundation for further improvement in phased array system.

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