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Centre-fed series array antenna for K-/Ka-band electromagnetic sensors

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Abstract: This study introduces a novel series array antenna for passive millimeter wave sensor applications, particularly physical securities and vigilance sensors. The antenna is mainly composed of a three-line series array and has a symmetrical structure whereby a 'Chebyshev polynomial' has been used to obtain a low side-lobe characteristic. For a more symmetrical antenna pattern, the authors considered a centre feeding structure from an input port to the three individual linear arrays. This feeding structure is very helpful when it comes to designing centre-fed and non-edge-fed multi-line linear arrays with low dividing losses. For the verification of the array design, the authors implemented the feeding structure to a K-band electromagnetic (EM) sensor antenna. This array was fabricated on a printed circuit board, and showed good performance to satisfy the required specification for an EM sensor. The authors designed another Ka-band array with the same structure as the K-band model, and found that the gain of the array can be increased by controlling the inclined angle of the side wings. Using the side wings, the authors were able to realise high gain performances in conformal size without variation in other types of performance.

1 Introduction

For antennas operating at high frequencies, superior fabrication tolerance, cost and efficiency – that are closely related to the antenna structure – are very challenging to achieve, as it can be very difficult to optimise these parameters simultaneously. A number of approaches have already been introduced in commercial and military use, including printed planar antennas, waveguide antennas, on-chip antennas and other novel types of antennas [1–11]. As operating frequencies increase to the millimetre wave (mm) scale, efficiency becomes an essential consideration [1]. Thus, special types of antennas, such as waveguide and horn antennas, are very good for the inherent structural benefit of low losses at higher frequencies. However, they have limitations in terms fabrication tolerance, miniaturisation and low-cost solutions.

In this paper, we propose a series array antenna using a novel centre feeding structure operating in the K- and Ka-band. The linear arrays are basically composed of N parallel elements, and the amplitude distribution for each element is decided by the Chebyshev polynomial to generate good side-lobe level (SLL) performance [3–11]. Even in high-frequency applications, the linear array is a good candidate for planar-type antennas because it can minimise the feeding loss generated in the feed network that creates a simple structure and short feed length. Thus, despite its inherent disadvantage of low radiation efficiency at high frequencies, the linear array is widely used in various radar and sensor applications. For high gain performance to enhance the operating range, we enlarged the single line linear array to three lines and designed a novel feeding structure. The feeding method is very efficient when it comes to distributing the antenna input power fed in a linear array to other arrays at the centre or the non-edge of the array. Thus, we could easily design a large linear array with a symmetrical beam pattern. In this design, we used a microstrip-type linear array structure for low fabrication costs. The substrate is RT-duroid 5880, and this is one of the most effective mm-wave circuit models because of its low dissipation factor and uniform dielectric constant.

As another option to increase the gain performance of the antennas, we used metallic side wings connected to both sides of the antenna ground plane. The inclined angle of the wings could be freely controlled from 0 to 90° in relation to the antenna ground plane, and we were able to enhance the antenna directivity using the optimal wing angle with minimal changes in other types of performance, particularly operating frequency and SLL. Thus, we were able to overcome the limited gain performance with a simple mechanic structure.

2 K-band single-line linear array design

Prior to the design of the multi-line centre-fed linear array, we created a single-line linear array with a ten-element antenna. This array was designed to satisfy the performance of a K-band electromagnetic (EM) sensor, as shown below:

- Antenna gain: 18 dBi (min.).
- Frequency band: 24.05–24.25 GHz.

- Half power beam width (HPBW): 5° on the *xz*-plane (min.), 90° on the *yz*-plane (min.).
- Polarisation: vertical linear.
- SLL: 17 dB (min.).

This array is centre fed and has two side wings to control the antenna directivity without any changes of other performances, especially SLL and return loss. The proposed array design is shown in Fig. 1. As shown in the figure, this antenna is the size of the overall printed circuit board (PCB) and has a length (AL) of 160 mm and width (AW) of 14.4 mm. The length (SL) and width (SW) of each side wing is exactly the same as the size of the patch array, specifically AL and AW. The antenna substrate is Rogers's RT/duroid 5880 ($\varepsilon_r = 2.3$) and its thickness is 0.5 mm. Each end of the array is terminated with a short through via holes and the total length of the feed array is 87.2 mm. The length from a short to the nearest patch is a quarter wavelength of the operating centre frequency, 24.15 GHz [12, 13]. The length of each patch (PL) is identical, at 4.1 mm. The lengths of the transmission lines (AG) between the patches are also identical, at 4.2 mm.

In the series array design, we chose a Chebyshev characteristic with a constant SLL of 20 dB. To obtain a flat SLL performance, we used amplitude coefficients modified from an ordinary Chebyshev synthesis and introduced a short at the last element for a constant current flowing through all the antenna elements. The width of the centre patch (PW) is 4.8 mm; the patch width is variable, with a ratio of 1, 0.92, 0.83, 0.55 or 0.7 from the array centre to the edge [3–5]. The array factor (AF) of the series array can be written as

$$(\mathrm{AF})_{2M} = \sum_{n=1}^{M=5} a_n \cos\left[(2n-1)u\right], \quad u = \frac{\pi d}{\lambda}\cos\theta \qquad (1)$$

Let $M = 5$

$$(\mathrm{AF})_{10} = 1.43\cos(u) + 1.32\cos(3u) + 0.83\cos(5u) + 0.79\cos(7u) + 1.0\cos(9u) \qquad (2)$$

where M is the half of the number of array elements and a_n is the amplitude coefficient of the nth element.

Fig. 1*b* shows the side view of the proposed antenna with two side wings. The wings are metal plates connected with the ground plane at the both sides of the array. The inclined angle of the wings (WA) can be changed; we examined the antenna performances according to the inclined angle of the wings. To verify the design feasibility, we measured the antenna performances in the anechoic chamber using the near-field system of NSI Inc. The measurements were carried out in the conditions of WA = 0 and 45°. The measured array gain increased as WA was increased. The measured antenna gains were 17.5 and 19.1 dBi and the SLLs were 17.4 and 17.5 dB at WA = 0 and 45°, respectively. The SLL of the antenna remained constant regardless of the WA. The HPBWs were 8.2 and 7.6° in the *xz*-plane and 82.1 and 79.8° in the *yz*-plane at WA = 0 and 45° [14]. Therefore we can confirm from the measurement

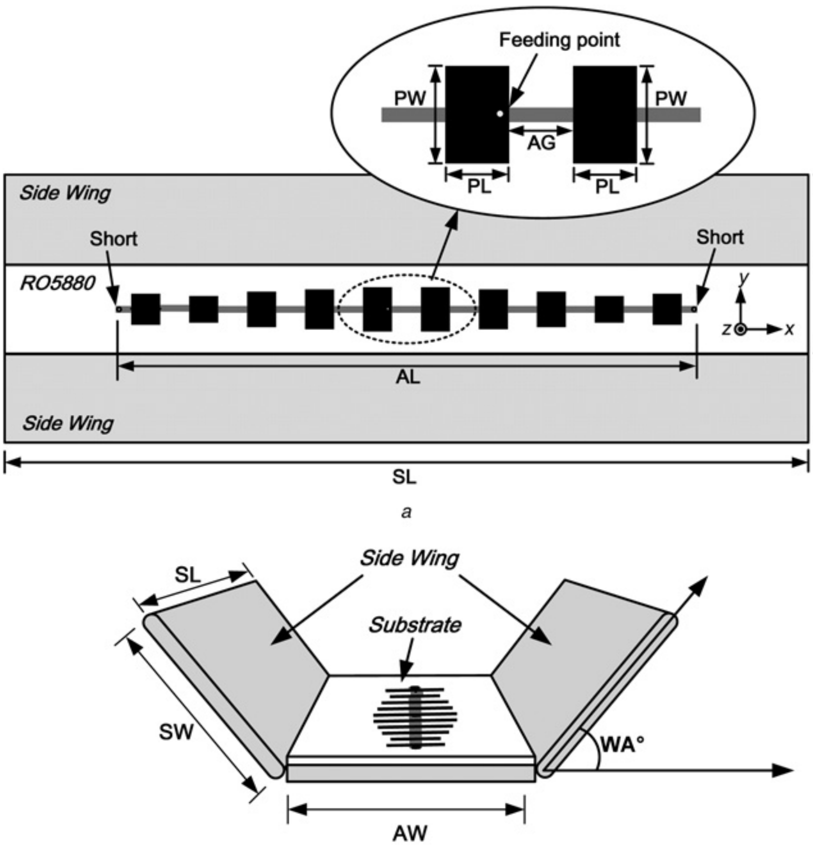

Fig. 1 *K-band single line linear array structure with side wings*
a Top-view
b Side view

Table 1 Measured results of the fabricated K-band single array antenna

Item		Inclined angle of side wings		Deviation
		0°	45°	
antenna gain		17.5 dBi (min.)	19.1 dBi (min.)	1.6 dB
frequency band		24.05–24.25 GHz		–
return loss		13.5 dB (min.)	13.5 dB (min.)	0 dB
SLL		17.4 dB (min.)	17.5 dB (min.)	0.1 dB
HPBW	*xz*-plane, degree	8.2	7.4	−0.8
	yz-plane, degree	86.5	72.7	−13.8

results that the centre-fed array exhibits good performance, and that the gain performance of the array can be increased as the inclined angle of the wings is increased. The measured results of the linear array are summarised in Table 1.

3 Multi-line centre-fed linear array design

3.1 K-band array

To extend the sensing range, we designed an enlarged linear array. The main specifications of the K-band three-line linear array are as follows.

- Antenna gain: 22 dBi (min.).
- Frequency band: 24.05–24.25 GHz.
- HPBW: 5° on the *xz*-plane (min.), 50° on the *yz*-plane (max.).
- Polarisation: vertical linear.
- SLL: 15 dB (min.) on the *yz*-plane.

Fig. 2 shows the proposed centre-fed three-line array structure operating in the K-band, that is composed of three linear arrays in parallel; the feeding point is placed in the centre patch element of the middle one of the array. To realise the symmetrical beam pattern, we considered a novel feeding structure to feed from the patch, including the feeding point to other centre patches. The proposed feeding structure was symmetrical on the right and left to enhance the symmetric pattern characteristic, because beam tilt can be the main cause of gain degradation in the antenna bore sight. The detailed feeding structure is shown in Fig. 3. To divide the input power (P_{IN}) fed from the feeding point on a centre patch (patch 1) to other centre patches (up: patch 2, down: patch 3), we used two three-way equal dividers on both sides of patch 1. On the right image shown in Fig. 3, the input power fed from the feeding point of patch 1 is P_{IN}. If we consider the radiating power (P_{rad1}) of patch 1, which is about 10% of the total input power of the patch (P_{IN}), the first dividing power on both sides of patch 1 (P_0) is 0.45 P_{IN}. The left image in Fig. 3 shows a basic three-way equal power divider. From this figure, if the input port impedance of P_0 is Z_0 and three output ports have the same impedance of $3Z_0$, the input power (P_0) can be equally divided into the output ports as P_1. Thus, the input power of the other patches is $2P_1$. Moreover, if we once again consider the radiating power (P_{rad2}) of patches 2 and 3, the output power of the patches to both sides (P_2) is about $2P_1 - 0.1(2P_1)$. Using the proposed power dividing structure, the detailed power distribution among patches 1–3 can be written as follows

$$P_0 = 0.5(P_{IN} - P_{rad1}) = 0.5(P_{IN} - 0.1P_{IN}) = 0.45P_{IN} \quad (3)$$

$$P_1 = 0.33P_0 = 0.15P_{IN} \quad (4)$$

$$P_2 = 0.5(2P_1 - P_{rad2}) = 0.5(0.3P_{IN} - 0.03P_{IN}) = 0.14P_{IN} \quad (5)$$

where

P_{rad}: 10% of the total input power fed in a patch,
$P_{rad1} = 0.1P_{IN}$,
$P_{rad2} = P_{rad2} = 0.1(2P_1) = 0.1(0.3P_{IN}) = 0.03P_{IN}$

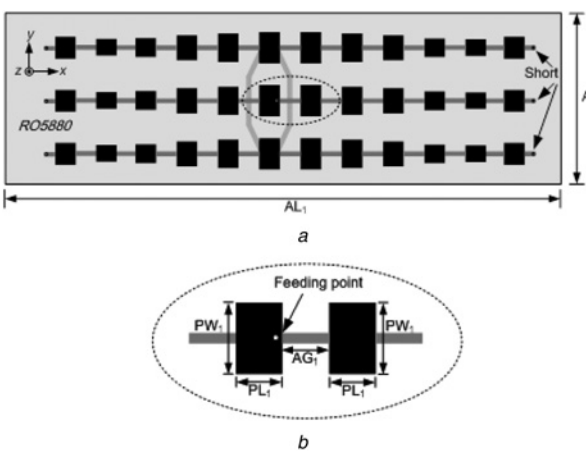

Fig. 2 *K-band centre-fed three-line linear array structure*

a Top view
b Detail dimension of the array structure

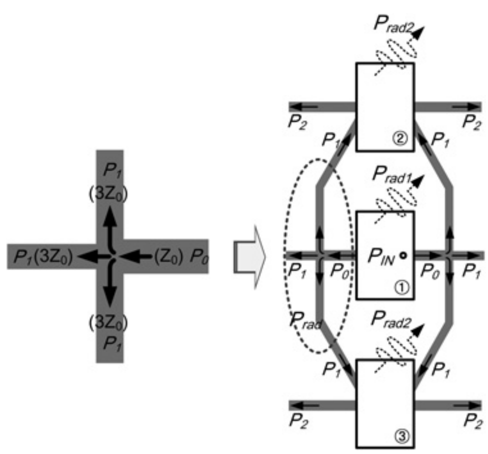

Fig. 3 *Centre feeding structure of the K-band three-line linear array*

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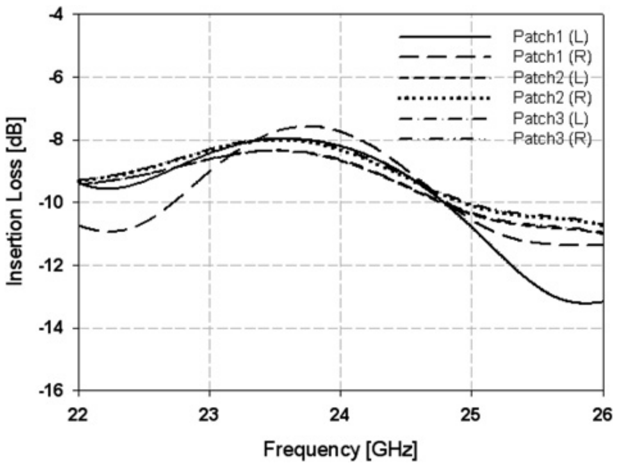

Fig. 4 *Simulation results of the insertion loss from the feeding point to the output ports for the proposed centre feeding structure*

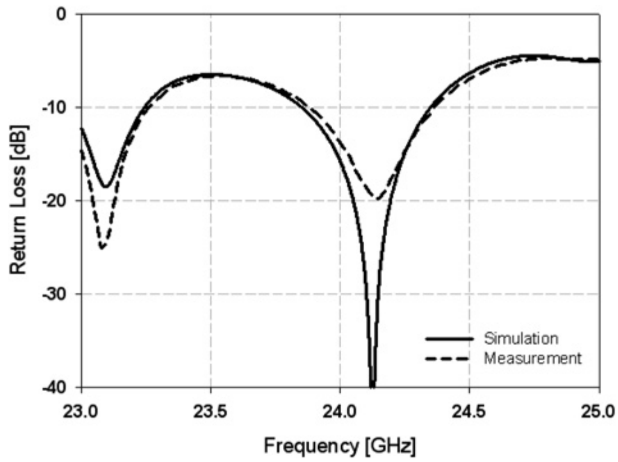

Fig. 5 *Simulated and measured return loss characteristic of the K-band three-line linear array*

From (4) and (5), we can determine that the output power of the centre patches (P_1, P_2) is nearly the same; thus, the power division among the centre patches is equal.

Fig. 4 is the simulation result of the proposed feeding structure for multi-line linear arrays, and shows the insertion loss from the feeding point to the output ports of the three patches illustrated in Fig. 3. From the results, it can be determined that the power division to all of the output ports is almost the same, and the radiation pattern is symmetric in all directions.

As explained above, we performed the simulation of the centre-fed three-line linear array depicted in Fig. 2 using the proposed feeding structure. All simulations were performed by a commercial EM calculation program, CST Microwave Studio®. Each linear array was composed of 12 element antennas and had a similar structure with the K-band single-line linear array described in Section 2. The radiating power distribution of all elements was decided by the modified Chebyshev polynomials [3–5], and could be controlled by patch width. The array factor of the linear array can be written as (6)

$$(\mathrm{AF})_{12} = 1.41\cos(u) + 1.34\cos(3u) + 1.20\cos(5u) + 1\cos(7u) + 0.77\cos(9u) + 1\cos(11u) \qquad (6)$$

The array was designed and fabricated using Rogers's RT/duroid 5880 ($\varepsilon_r = 2.3$) with a thickness of 0.5 mm. Overall PCB size was 100 mm (AL_1) ×30 mm (AW_1). The length of each patch (PL_1) and the transmission line (AG_1) were 4.08 and 4.2 mm, respectively. Each patch width (PW_1) of the linear array was proportional to the coefficients of the array factor in (6). Thus, the ratios of the patch width, in order, were 1, 0.95, 0.85, 0.71, 0.55, 0.71 from the centre patch to the edge.

Figs. 5 and 6 show the simulated and measured results, respectively, of the K-band three-line linear array (Table 2) with the proposed feeding structure. From the results, we can determine that the operation frequency of the array is 23.8–24.4 GHz at 10 dB. Also, the minimum antenna gain is 22.3 dBi with HPBWs of 6.8 and 27.4° for the *xz*- and *yz*-plane. In addition, the maximum SLLs are 16.9 and 17.4 dB for the *xz*- and *yz*-plane. The performance test was performed in the anechoic chamber of Orbit FR, Inc. and all measured results are well matched with the simulation results. The fabricated K-band three-line linear array is shown in Fig. 7.

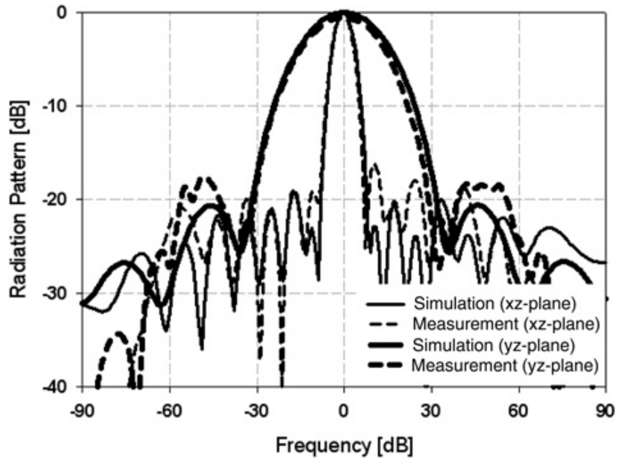

Fig. 6 *Simulated and measured radiation pattern of the K-band three-line linear array*

3.2 Ka-band array

The Ka-band is also widely used in high-resolution and close-range targeting radars for vigilance and speed detection. The proposed linear array structure of the K-band was applied in Ka-band sensor application (Table 3). In doing this, we wanted to determine the application possibility of the proposed linear array, including the centre feeding structure and the metallic walls, in the Ka-band. The target

Table 2 Measured results of the K-band three-line linear array

Item		Measured results (without wings)
antenna gain		22.3 dBi
frequency band		24.05–24.25
return loss		12.8 dB (min.)
SLL		16.2 dB (min.)
HPBW	*xz*-plane	6.8°
	yz-plane	27.4°

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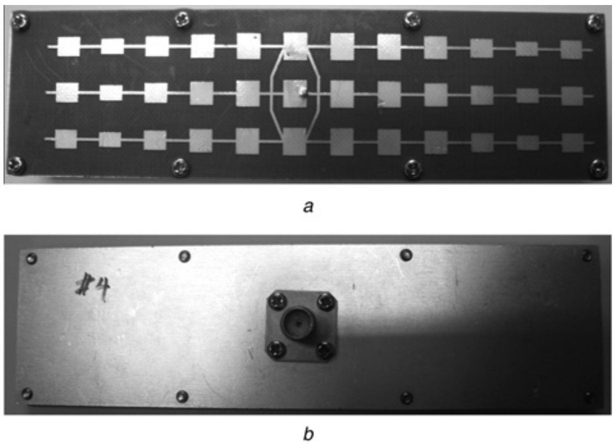

Fig. 7 *Fabricated K-band three-line linear array with input connector*

a Front side
b Back side

Table 3 Measured results of the Ka-band three-line linear array

Item	Existence of side wings		Deviation
	Without wings	With wings	
antenna gain	19.7 dBi (min.)	21.3 dBi (min.)	1.6 dB
frequency band	34.0–34.7 GHz		–
return loss, dB	10.5	12.0	1.5
SLL			
xz-plane, dB	15.6	16.5	0.9
yz-plane, dB	30	28.1	−1.9
HPBW			
xz-plane, degree	5.4	5.5	0.1
yz-plane, degree	26.7	20.1	−6.6

performance of the Ka-band linear array is given briefly below:

- Antenna gain: 20 dBi (min.).
- Frequency band: 34.0–34.7 GHz.
- HPBW: 5° in azimuth (min.), 50° in elevation (max.).
- Polarisation: vertical linear.
- SLL: 15 dB (min.) in azimuth.

All array design concepts are the same as those of the K-band three-line linear arrays discussed in the previous section; the whole array structure was rescaled to the operating frequency of the Ka-band. The radiating power envelope of the 12-element linear array was decided by the Chebyshev polynomials and the array factor of the array was the same as in the K-band model. The whole array size was 74 mm × 30 mm without wings. In this design, we found the optimal inclined angle of the metal wings to be 90°. In this design, the Ka-band linear array is composed of three linear arrays, and the beam width in the elevation direction (the y-axis in Figs. 2 and 3) is narrower than the single-line linear array. Thus, if we want to obtain the effect of the side wings in terms of directivity, it is helpful to have a steep inclined angle of the wings. In addition, the wing's size should be determined such that the antenna radiating power is scattered in the walls. From the simulation, we decided that the size of the wings was 74 mm × 20 mm and the optimal inclined angle was 90°. The antenna substrate was Rogers's RT/duroid 5880.

The simulated and measured performance results of the Ka-band linear array are shown in Figs. 8 and 9. From

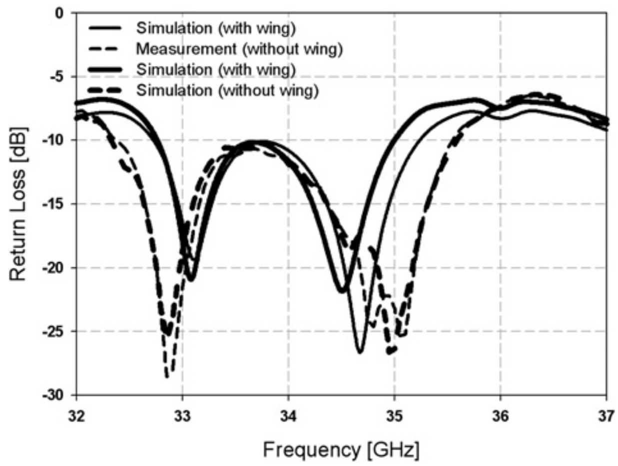

Fig. 8 *Simulated and measured return loss characteristic of the Ka-band three-line linear array with the proposed centre feeding structure*

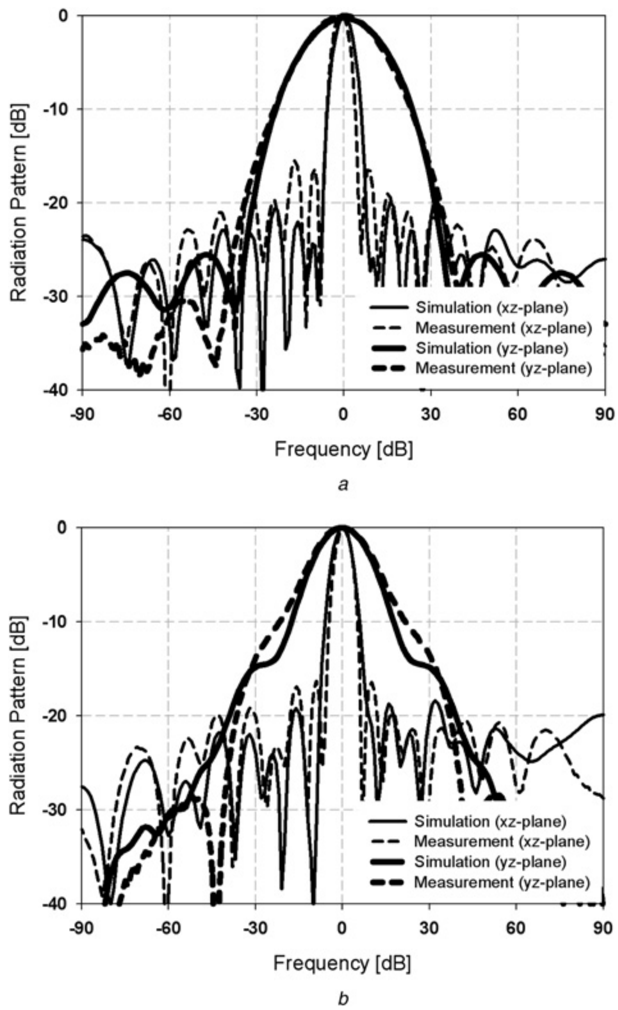

Fig. 9 *Simulated and measured radiation pattern characteristics of the Ka-band three-line linear array and the proposed centre feeding structure*

a Without wings
b With wings

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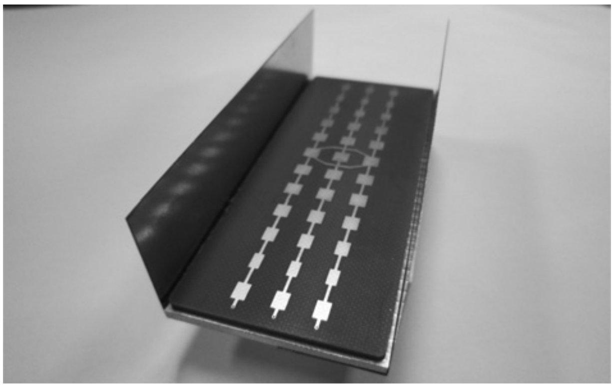

Fig. 10 *Fabricated Ka-band three-line linear array with metal wings*

Fig. 8, it can be known that the operating frequency is 32.0–35.5 GHz at 10 dB reference and the return loss has no effect of the existence of the side walls. Fig. 9 shows the simulated and measured radiation patterns at the centre frequency, 34.4 GHz. The antenna gains of the array with and without wings were 19.7 and 21.3 dBi. Also, the HPBW of the array changed from 5.4 to 6.5° in the *xz*-plane and 25.3 to 20.1° in the *yz*-plane when wings were used. The SLL was about 15.6 dB in the *xz*-plane without wings and the performance was maintained when wings were present. Thus, we were able to enhance the limited gain of the linear array using the wings by 1.1 dB without any change in return loss or SLL performance. The fabricated Ka-band three-line centre-fed array is shown in Fig. 10.

4 Conclusion

This paper introduced a series array antennas using a novel centre feeding structure operating in the K- and Ka-band. First, we designed a 10-element single-line linear array with metallic side wings in the K-band, and the amplitude distribution for each element was decided by a Chebyshev polynomial to obtain SLL performance. Using the metal wings, it was confirmed that the antenna gain can be increased while maintaining other types of performance such as operation frequency, return loss and SLL. Second, we enlarged the single-line linear array to a three-line linear array structure. In this antenna design, we proposed a novel centre feeding structure that could distribute the input signal power fed in the centre array to the other arrays with a very simple structure. The feeding structure was composed of two three-way dividers on both sides of the feeding point, and we were able to easily realise equal or unequal power distribution by changing the port impedance. Finally, we applied the proposed array design to Ka-band applications. The Ka-band array had the same structure as the K-band three-line linear array with metallic side wings. This array exhibited good performance in highly sensitive Ka-band sensor application, and the antenna gain was enhanced by the side wings. Thus, the proposed linear array can be widely used in millimetre-wave applications that require a simple structure with low fabrication cost.

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