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Wideband Balanced Antipodal Vivaldi Antenna with Enhanced Radiation Parameters

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Abstract—A novel balanced antipodal Vivaldi antenna (BAVA) with high gain and enhanced radiation parameters is proposed in this paper. The outer edges of the flare are modified by a binomial curve to broaden the impedance bandwidth. A modified metal director is adopted to improve the antenna gain and beam-tilting. The measured results show that the proposed BAVA achieves a bandwidth from 2 to more than 40 GHz with peak gain > 0 dBi and > 1 dBi over the 8–40 GHz range. The squinting beam of E-plane is less than 5° from 4 to 40 GHz and less than 3° from 22 to 40 GHz.

1. INTRODUCTION

Antennas, especially ultra-wideband (UWB) antennas with good performances, have attracted a lot of attention since the FCC authorized the unlicensed commercial application of UWB communication system from 3.1 to 10.6 GHz [1]. In recent years, many studies on UWB antenna design have been published, including planar monopole antennas [2], printed antenna [3], and leaky lens antenna [4], etc. Among the reported wideband antennas, the Vivaldi antenna is often preferred for its satisfactory radiation characteristics and simple structure

The conventional Vivaldi antenna is one of the tapered slot antennas developed by Gibson in 1979 [5]. In order to broaden the operation bandwidth, Gazit proposed the antipodal Vivaldi antenna (AVA) in 1988 [6]. Compared with the conventional Vivaldi antenna and AVA, the balanced antipodal Vivaldi antenna (BAVA) introduced by Langley et al. [7] has relatively low cross-polarization. The BAVA has many excellent performances including producing a symmetrical beam in the E-plane and H-plane and having good directivity and high gain. Various methods and structures have been proposed to design Vivaldi antennas with good radiation characteristics [8–18]. In [8], the antenna gain and directivity were improved by the inclusion of a director consisting of a profiled piece of higher dielectric constant material in the antenna aperture. However, it adds complexity to the fabrication process and increases antenna weight. In [9], a new composite exponential curve was used to achieve a better gain performance in the whole operating frequency band. A dielectric lens was adopted in front of the antenna's aperture to improve the beam-tilting in E-plane within the UWB frequency range [10]. In [11], a novel BAVA was presented based on the substrate end shaping. In addition, corrugation at the flares has been widely used to improve the performance of Vivaldi antenna such as gain [12–15]. In [16], the SIW technology was used to achieve a compact Vivaldi antenna and broaden its operational bandwidth. A reconfigurable wideband Vivaldi antenna was presented in [17]. In order to generate narrowband multiples, the ring slot pairs was adopted. In [18], the directivity and gain of the proposed AVA were improved based on introducing a parasitic elliptical patch in the flare aperture. Nevertheless, no obvious improvement was obtained on the antenna gain at high frequencies (> 25 GHz).

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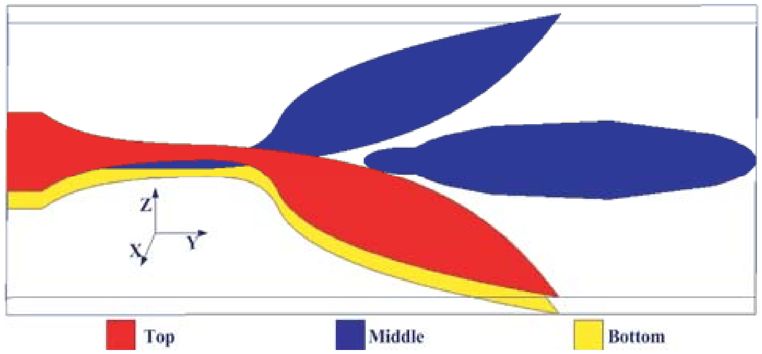


Figure 1. Layout of the proposed modified BAVA with a modified director (MBAVA-MD).

In this paper, a novel broadband BAVA with high gain and improved beam tilting is presented and shown in Fig. 1. At first, the outer edges of the tapered radiation flare are modified by a binomial curve and an exponential curve. As a result, an extremely wide impedance bandwidth is obtained. Moreover, a parasitic compounded elliptical metal patch called director is inserted in the center of the antenna aperture to enhance field coupling between the flares and direct most of the energy toward the aperture center. Therefore, the antenna produces stronger radiation in the endfire direction, and the beam-tilting in E-plane is significantly improved. A prototype of the proposed antenna has been fabricated and measured for verification. The results show that the proposed antenna can achieve a very wide operating bandwidth with good radiation characteristics

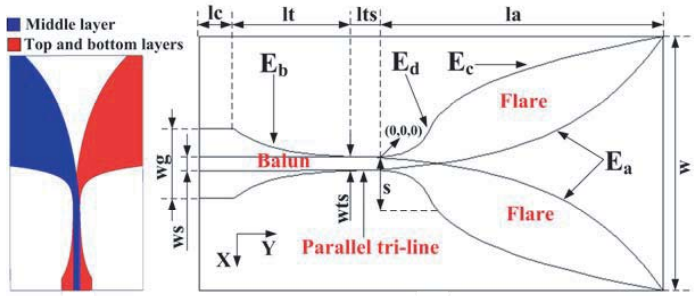
2. THE DESIGN AND ANALYSIS OF THE PROPOSED BAVA

Vivaldi antenna is also known as exponential tapered slotline antenna (ETSA), which belongs to the end-fire travelling wave antennas category. Compared with the conventional Vivaldi antenna and AVA, the BAVA has a more compact profile, much wider bandwidth and relatively low cross-polarisation. The radiation characteristic of the BAVA is mainly determined by the aperture width (the distance between the flares). At low frequencies, the Vivaldi antenna operates as a resonant antenna, and its lowest operating frequency is determined by the maximum width of the antenna aperture ($\sim \lambda/2$). However, it mainly operates as traveling wave radiator at high frequencies. Depending on different widths, the flare radiates at different frequencies. Therefore, the operational bandwidth of Vivaldi antenna is unlimited theoretically. In practice, as the frequency increases, different issues occur, which degrade the radiation properties. For example, the beam-squinting mainly caused by the difference in the dielectric loading of the ground flares (top and bottom layer) compared to the signal flare (middle layer) and the unbalanced current distribution after the transition from the stripline to the start of the flares [19] result in bad directivity in high frequencies. Besides, the phase reversal of current traveling along the flare at high frequencies and some undesired radiation also severely deteriorate the radiation properties of BAVA.

In summary, it is hard to obtain a BAVA operating at a UWB frequency range with satisfactory performances. Therefore, some effective measures need to be adopted to mitigate the influence mentioned above.

Figure 2 shows two designs of the antennas, including the conventional balanced antipodal Vivaldi antenna (CBAVA) (Fig. 2(a)) and modified balanced antipodal Vivaldi antenna (MBAVA) (Fig. 2(b)). The basic structure of the proposed MBAVA is shown in Fig. 2. The modified balanced antipodal Vivaldi antenna mainly consists of three parts. The first part is a tapered balun fed structure adopted to obtain balanced feed for the antenna. The second one is parallel tri-line providing wideband transitions. The third one is the radiation flare including the ground flares (top and bottom layer) and signal flare (middle layer).

For the tapered balun, the central layer (the conductor) width decreases linearly from ws to wts;



(a) (b)

Figure 2. (a) Structure of the conventional BAVA (CBAVA). (b) Plan of the proposed modified BAVA (MBAVA).

the outside edges of the top and bottom layers are described by E_b as follows:

$$E_b\colon x = A_b \cdot e^{b \cdot y} + B_b \tag{1}$$

where A_b and B_b are defined by Eq. (2).

$$\begin{cases} A_b = \dfrac{wts - wg}{2A_{b1}} \; B_b = -A_b \cdot e^{-\,\mathrm{c}\cdot \mathrm{lts}} \\ A_{b1} = e^{-\,\mathrm{c}\cdot\mathrm{lt}+lts)} - e^{-\,\mathrm{c}\cdot lts} \end{cases} \tag{2}$$

For the modified flare, the inner edges of the flare are defined by an exponential curve (E_a) shown in Eq. (3).

$$E_a\colon x = A_a \cdot e^{a \cdot y} + A_a \tag{3}$$

$$A_a = B_a = \frac{wa + wts}{2 \cdot (e^{a \cdot la} - 1)} \tag{4}$$

In this work, the outer edges of the radiation flare are modified by two curves (E_c and E_d) defined by Eq. (56). As a result, the lower operating frequency is reduced by the widened end structure introduced by the curve (E_c). Moreover, the sharp edge resulting in wave diffraction at the start of the flare is effectively avoided

$$E_c\colon x = A_c \cdot y^3 + B_c B_c = la - A_c \cdot \left(\frac{wa + wts}{2}\right)^3 \tag{5}$$

$$E_d\colon x = A_d \cdot e^{d \cdot y} + B_d B_d = wts - A_d \tag{6}$$

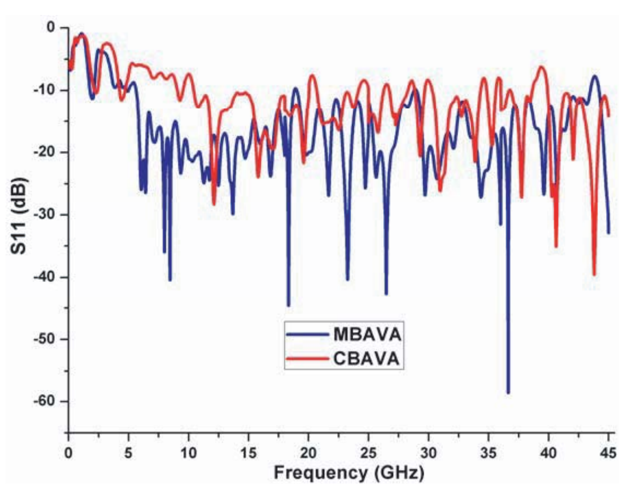


Figure 3. Simulated S_{11} for the MBAVA and CBAVA.

Figure 3 shows the simulated S11 for the CBAVA and MBAVA. As mentioned above, for the MBAVA, the outer edges of the tapered radiation flare are modified by a binomial curve and an exponential curve to obtain an extremely wide impedance bandwidth. Clearly, the MBAVA has a better return loss than CBAVA especially in low frequencies.

As mentioned above, several factors could degrade the performance of BAVA. Among them, dropping antenna gain, splitting beam and tilting beam in high frequencies are most serious. In order to further improve the antenna performance, an elliptical metal patch placed in the middle layer of the antenna is used as shown in Fig. 4. The metal patch could direct most of the energy toward the aperture center so as to improve beam-tilting. Meanwhile, the field coupling between the flares is enhanced so that the antenna gain is increased significantly, especially in high frequencies.

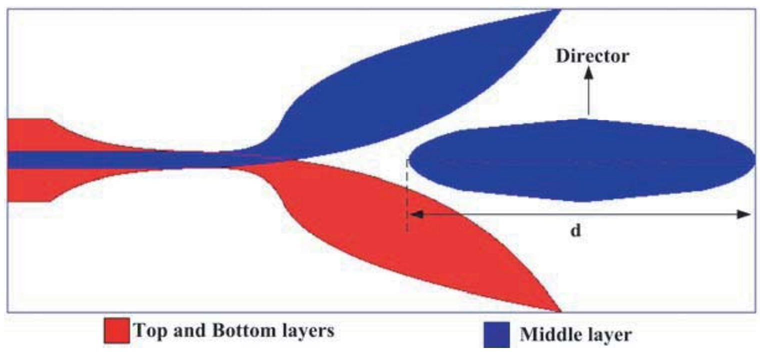


Figure 4. Layout of the proposed modified BAVA with a director (MBAVA-D).

As shown in Fig. 5, the antenna gain for MBAVA-D is improved significantly in middle-high frequencies. And parameter d is found to have significant impact on the gain performance with the gain change increasing nearly 5 dB as d increases from 30 to 50 mm in middle-high frequency (> 20 GHz). However, further increase in d causes the gain to decrease in high frequencies (> 30 GHz). Besides, a more increase of parameter d will result in a very long antenna extension, which is not suitable for practical applications.

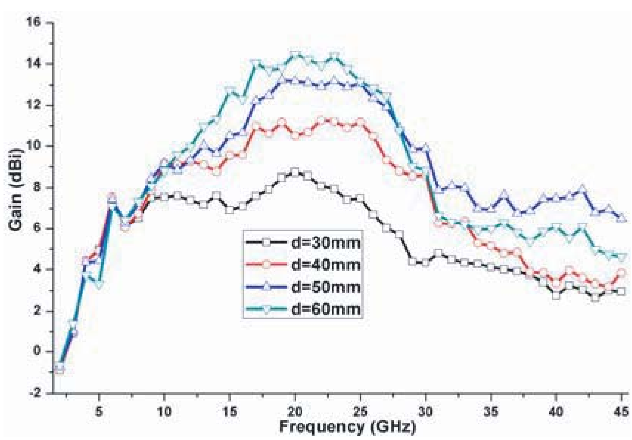


Figure 5. Simulated gain for MBAVA-D with different d.

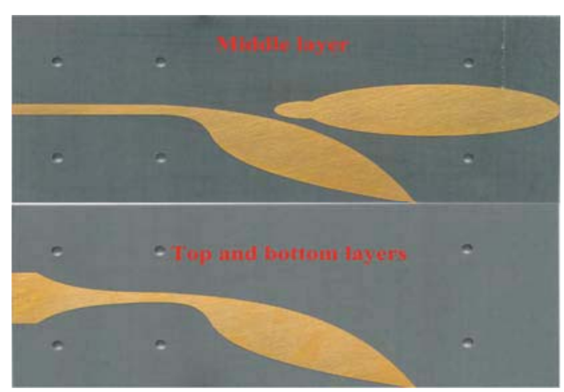


Figure 6. Photographs of the fabricated MBAVA-MD.

Even though the antenna gain is enhanced by the metal director, the improvement on the antenna gain is limited to the frequency band up to 30 GHz with relatively low gain. In this work, to further improve the antenna in a higher frequency band, a modified director is proposed as shown in Fig. 1. Compared with the traditional director used in MBAVA-D and antipodal Vivaldi antenna (AVA) [18], this novel director has some distinct advantages. The single elliptical metal patch is replaced by a compounded elliptical patch consisting of a large elliptical patch and a smaller one. As a result, the field coupling near the start of the flare, which radiates at high frequencies, could also be enhanced. In a word, the improvement on antenna gain could also be achieved in a higher frequency band. Besides, the modified director is inserted in the middle layer of BAVA. Therefore, the proposed antenna has a better cross-polarization than the AVA [7].

3. EXPERIMENTAL RESULTS

According to the above analysis, the MBAVA-MD has been designed. As shown in Fig. 6, a prototype of the proposed BAVA has been fabricated on Rogers RT/duroid 5880. The substrate has a relative permittivity 2.2 and thickness 3.0 mm. The antenna is simulated and optimized using commercial software CST Microwave Studio TM. The final dimensions of the fabricated MBAVA-MD are (see Fig. 7): $wg = 12\,\text{mm}$, $wts = 2.24\,\text{mm}$, $ws = 2.43\,\text{mm}$, $lc = 4\,\text{mm}$, $lt = 23\,\text{mm}$, $lts = 1\,\text{mm}$, $la = 50\,\text{mm}$, $w = 44\,\text{mm}$, $a = 0.06$, $b = -0.15$, $d = 0.4$, $s = 8\,\text{mm}$, $A_d = 0.1$, $a_2 = 7.4\,\text{mm}$, $b_2 = 2\,\text{mm}$, $d = 21.8\,\text{mm}$, $b_1 = 5.4\,\text{mm}$, $a_1 = 24\,\text{mm}$.

S_{11} of the fabricated balanced antipodal Vivaldi antenna was measured with Agilent Performance Network Analyzer N5225A. As can be seen from Fig. 8, S_{11} is less than -10 dB from 3 GHz to 40 GHz,

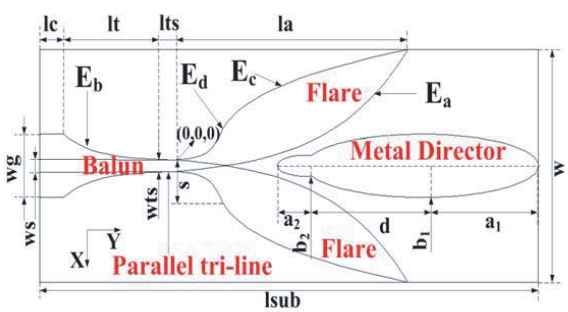


Figure 7. Dimensions of the proposed MBAVA-MD.

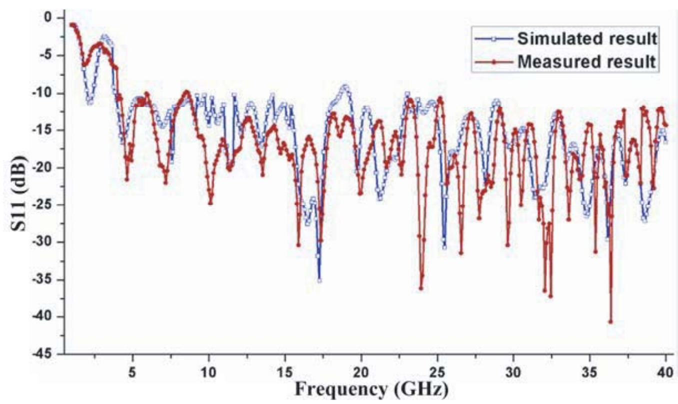


Figure 8. Simulated and measured S_{11} of the proposed MBAVA-MD.

Table 1. Squinting beam and E-plane cross-polarization.

Frequency (GHz)	Conventional BAVA		Proposed MBAVA-MD	
	Squinting beam, deg	cross-polarization, dB	Squinting beam, deg	cross-polarization, dB
4	−16	−16	−6	−25
8	−7	−15	−5	−24
12	−4	−17	−4	−27
16	10	−18	5	−26
20	29	−20	4	−33
24	26	−14	3	−26
28	48	−16	2	−22
32	42	−15	2	−25
36	38	−13	2	−23
40	35	−10	2	−18

and the measured and simulated results are in good agreement.

Within the frequency range from 4 to 40 GHz, quantitative comparisons of the squinting beam and the cross-polarization of E-plane in boresight direction are shown in Table 1. For conventional BAVA (CBAVA), the squinting beam is more than 25° for frequencies higher than 20 GHz, but the beam squinting of the proposed MBAVA-MD is less than 6° from 4 to 40 GHz (< 4° for frequencies higher than 20 GHz), which shows that the proposed MBAVA-MD has firmer resistance on beam tilts

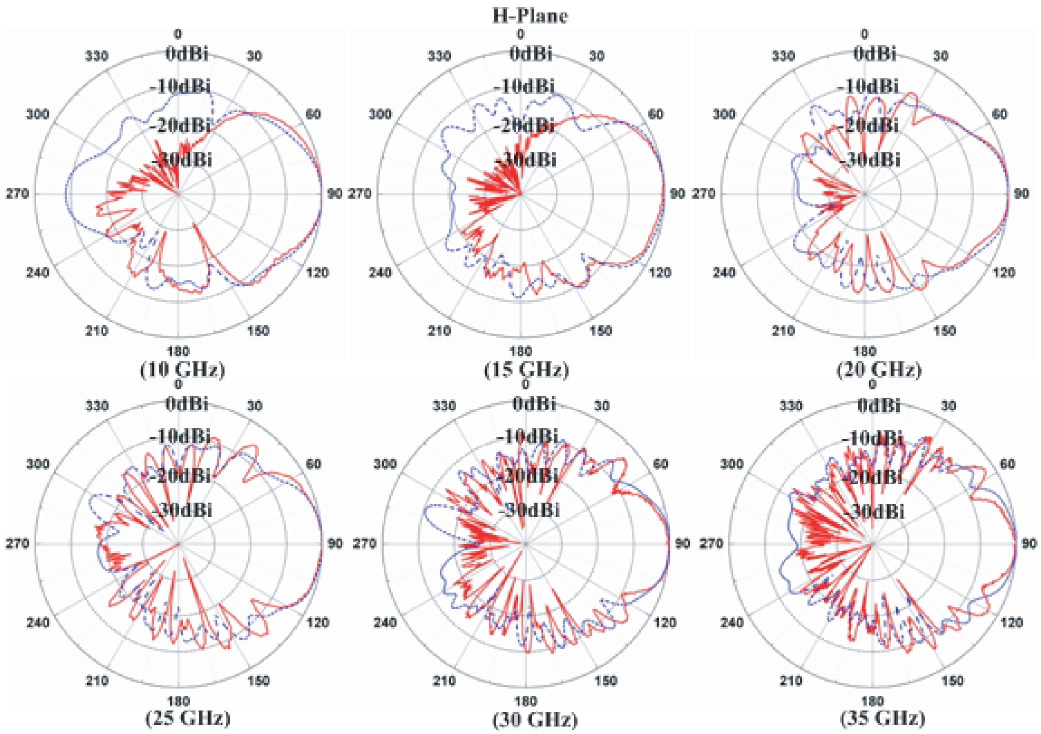


Figure 9. The measured (solid line) and simulated (dashed line) radiation patterns of H-plane at 10, 15, 20, 25, 30, 35 GHz.

Table 2. Comparison of the proposed antenna with literature.

Ref.	Dimensions (mm^3)	Relative permittivity	O.B.W. (GHz)	Freq. (GHz) → Gain (dBi)
[8]	80 × 44 × 9.2	2.94	2.4–18	N.M
[11]	56 × 105 × 3	2.5	6.0–20	6 → 9, 20 → 11
[12]	45 × 40 × 0.8	4.4	2.9–12	5 → 6, 11 → 7
[13]	40 × 80 × 0.508	3.38	3.4–40	N.M
[14]	42 × 36 × 1.6	4.4	3.7–18	6 → 5.4, 10 → 10, 18 → 5.4
[15]	50 × 66.4 × 1	4.5	4.0–30	4 → 5, 20 → 7.2, 30 → 5
[17]	92 × 106 × 1.6	4.7	1.5–5	N.M
[18]	66 × 140 × 1.5	2.94	2.0–32	10 → 11, 20 → 10.2, 30 → 5
[19]	50 × 166 × 3.15	2.55	3.0–18	3.5 → 2, 18 → 12
This work (MBAVA-MD)	44 × 98 × 3	2.2	2–> 40	10 → 11.2, 20 → 14.6, 40 → 10.5

'O.B.W.' states the operating bandwidth; 'N.M' represents the not mentioned.

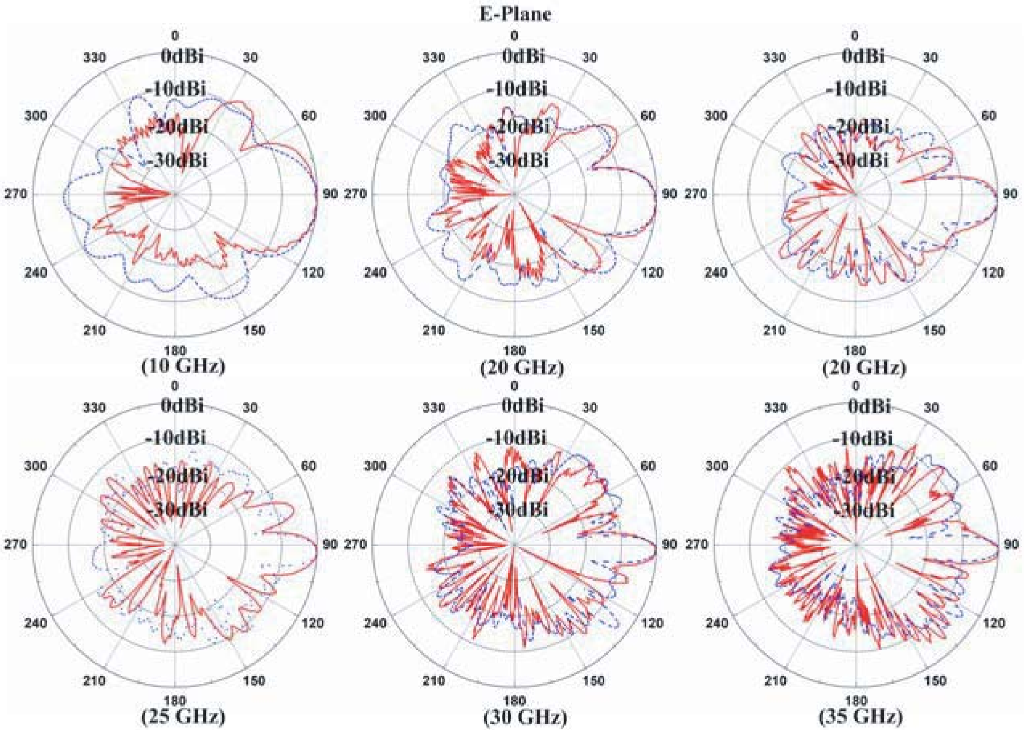


Figure 10. The measured (solid line) and simulated (dashed line) radiation patterns of E-plane at 10, 15, 20, 25, 30, 35 GHz.

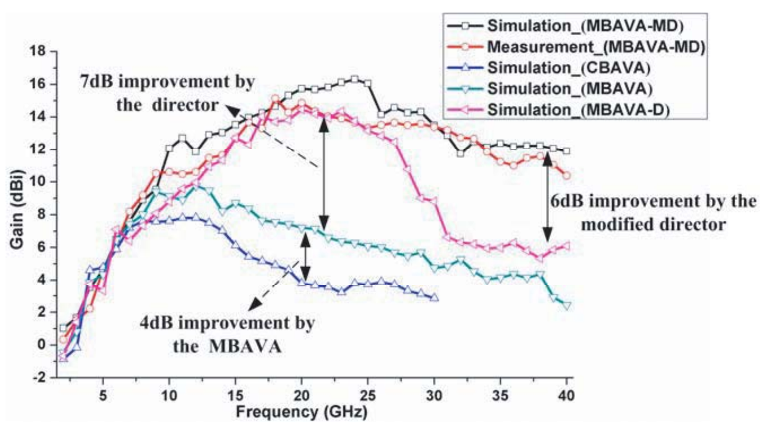


Figure 11. Simulated and measured gain the proposed BAVA.

at upper frequency band. In addition, the proposed MBAVA-MD has a better cross-polarisation than the conventional BAVA.

The measured H-plane and E-plane radiation patterns of the antenna at 10, 15, 20, 25, 30, 35 GHz are shown in Fig. 9 and Fig. 10, respectively. Clearly, the proposed MBAVA-MD has a satisfactory endfire radiation pattern directing in the axial direction of the antenna aperture (Y-direction seen in Fig. 1). Besides, both the E-plane and H-plane radiation patterns are symmetrical. The bandwidth of side lobe decreases as the frequency increases. As mentioned above, in high frequencies, some undesired radiation occurs which will cause the beam splits.

The simulated and measured peak gains of the proposed MBAVA-MD are shown in Fig. 11. Results indicate that the proposed antenna has good gain characteristics, and the gain is greater than 11 dBi over a very wide frequency range (12 to 40 GHz) and more than 13 dBi from 16 to 32 GHz. Clearly, the MBAVA has 4 dB improvement of gain relative to the conventional BAVA (CBAVA). In addition, compared with the MBAVA, the modified balanced antipodal Vivaldi antenna with a director (MBAVA-D) has a better gain characteristic with the gain change increasing nearly 7 dB in middle-high frequencies (15–25 GHz). Besides, the antenna gain is further increased about 6 dB owing to the modified director in high frequencies (> 30 GHz).

Table 2 lists the comparisons in terms of size, operation bandwidth, relative permittivity, and gain between the proposed antenna and antennas from literature. Clearly, the proposed antenna has some distinct advantages such as very wide operation bandwidth, high gain and relatively compact size.

4. CONCLUSIONS

In this paper, a very broadband BAVA is analyzed and designed. The radiation flares are modified by two curves to obtain an extremely large impedance bandwidth (the return loss better than 10 dB from 3 to 40 GHz). The beam tilts of E-plane are mitigated. Moreover, the antenna gain in high frequencies (> 30 GHz) is also improved by introducing a modified director. Finally, a prototype of the MBAVA-MD is measured in experiment. The results show that the proposed antenna has excellent performance such as satisfactory directivity, good endfire characteristic, low cross-polarisation, relatively high gain (> 11 dBi in the frequency range of 12 to 40 GHz and > 13 dBi from 16 to 32 GHz) and very wide operational bandwidth (2 to 40 GHz), which make the proposed antenna meet the requirements applied in phased array, UWB communication, etc.

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