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Research Article

Wideband antipodal Vivaldi antenna with enhanced radiation parameters

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Abstract: A modified broadband antipodal Vivaldi antenna for the operating frequency range of 6–18 GHz is presented. In order to eliminate diffraction from sharp ends, the corners of the patches are rounded. As a result, both the gain and directivity are improved. Moreover, one major addition that is done to the antenna is the background plane. The purpose of the backplane, which is made of metal, is to reflect any radiation going in a direction opposite to that of the required. This would then effectively increase the forward radiation, thus contributing to the gain of the antenna structure. In addition to be small in size, the designed antenna exhibits stable radiation patterns over the entire operating bandwidth, relatively high gain of 7–8.4 dB, and low cross-polarisation. A prototype of the modified antenna is fabricated and verified experimentally. The measured results are in reasonable agreement with the simulation data. Based on the obtained results, the designed antenna can be useful for broadband applications.

1 Introduction

Vivaldi antennas have been widely utilised for modern communication in both military and civil applications such as high-speed wireless communication [1], ground penetrating radar [2], phased array radars [3], radio astronomy [4], biomedical microwave imaging systems [5], and reflector feed [6]. These numerous applications are due to some features such as wide bandwidth, relatively high gain, high efficiency, symmetric beam in *E*- and *H*-planes, simple structure, low profile, low cost, and light weight [7, 8].

A tapered slot antenna (TSA) with exponential profile was first introduced by Gibson in 1979 [9], namely Vivaldi antenna. It is a travelling-wave endfire planar antenna which has a wide impedance bandwidth. In [10], by applying further layers of dielectric and metallisation, a new wideband triplate balanced antipodal Vivaldi antenna (AVA) with low cross-polarisation was presented and discussed for the first time. In [11], an efficient, full wave method of moments analysis program was used to study the effects of various design parameters on the performance of wideband Vivaldi notch-antenna arrays. A very wideband Vivaldi antenna with bandwidth ratio up to 9:1 based on a slot-line feed structure, a bowtie horn, and a rolled edge termination was developed, analysed and measured in [12].

However, the radiation patterns of a conventional Vivaldi antenna with bandwidth up to multiple-octave or one-decade are not stable over the entire operating bandwidth and the main beams at higher frequencies will split, leading to a reduction of the antenna gain [13–15]. The operating frequency range of the conventional Vivaldi antenna is restricted by the feeding structure and the width of the slot-line [16]. To overcome the drawback, Gazit [17] proposed an AVA in 1989. Afterwards, to improve the performance of the Vivaldi antenna various approaches were proposed. In [18], using corrugated radiator and ground plane of elliptical shapes, a miniaturised planar antenna of ultra-wideband (UWB) performance was presented. A novel compact end-fire AVA for UWB applications such as microwave imaging and high data rate wireless systems was proposed in [19]. To make the antenna compact, a bending feed line structure and sinusoidal modulated Gaussian tapered slot was used. One of the recent important applications of this type of directional antenna is medical imaging. A wideband microwave system including an array of 16 corrugated TSAs for head imaging was presented in [20]. In [21], a cavity-backed Vivaldi antenna for microwave breast measurements was designed. In [22] a photonic bandgap structure that is formed by micromachining the substrate with holes is used to improve the directivity. Also, a photonic bandgap structure, which is composed of horizontal slots on the metal patches and conductor strips at the bottom of the substrate, was employed to reduce the antenna side lobe and improve the front-to-back ratio [23]. Another effective method, investigated in [24], uses the electromagnetic bandgap structure as defected ground structure to reduce the antenna size, increase the bandwidth and improve the antenna matching while keeping the other performance within the operating band almost unchanged. In [25] a double-slot structure is proposed to develop a Vivaldi antenna with improved gain in a UWB. The double slot structure makes the aperture field distribution at the end of the antenna more uniform, thus the gain of the proposed antenna is higher than that of a conventional Vivaldi antenna with the same size. In [26], a slot loading exploited as a new termination of conventional Vivaldi antennas is introduced to increase impedance bandwidth as well as keep antenna geometry compact. A simple technique, based on the substrate end shaping, is used to enhance the gain and radiation pattern of AVA in [27]. A useful review on this type of antenna is given in [28]. Also, an applicable set of references on the AVA with several forms like linear TSA, constant-width TSA, parabolic TSA, Fermi TSA, logarithmically TSA, dual exponentially TSA and so on, can be found in [29].

The aim of this paper is to design a wideband Vivaldi antenna with simple structure and satisfactory radiation characteristics for practical applications. The designed AVA simultaneously covers the operations in the C, X and Ku-bands from 6 to 18 GHz. The ends of the patches are rounded to eliminate diffraction from corners. Consequently, both the gain and directivity are improved. Besides, to further enhance the gain and front-to-back ratio, a background plane is added to the antenna structure. The designed antenna exhibits several advantages such as small size, low cross-polarisation, low voltage standing wave ratio (VSWR), relatively high gain of 7–8.4 dB, and stable radiation patterns over the entire operating bandwidth which make this antenna suitable for use in broadband applications. A prototype of the modified antenna is fabricated and experimentally studied. The simulation results are in good agreement with the experimental data.

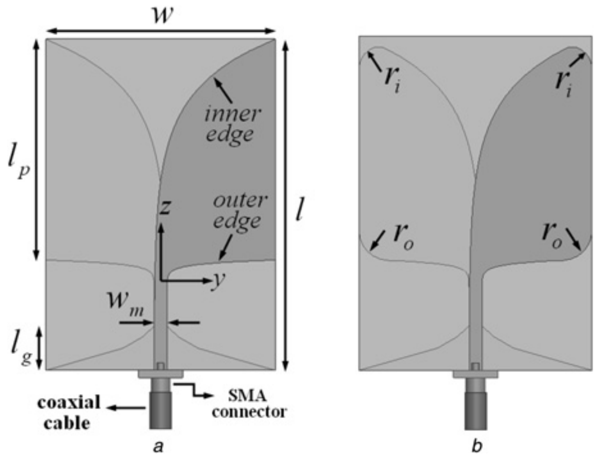

Fig. 1 *Configurations of the designed AVAs*
a Conventional AVA
b Improved AVA

2 Antenna configuration and design

Fig. 1 illustrates the structures of the designed AVAs. The configuration of the conventional AVA is demonstrated in Fig. 1*a*. Two metal patches of the AVA are located on two opposite sides of the dielectric substrate. They are flared in the opposite direction to form the radiation flares. The AVA is printed on a RO4003 substrate ($\varepsilon_r = 3.55$, tan $\delta = 0.0021$) with a thickness of 0.813 mm. The total size of the designed AVA is 31.2 mm × 45 mm. The designed antenna is fed by a microstrip line, while the feed-line width is set to be 1.7 mm in order to match the 50 Ω SMA connector. The inner and outer edges of the tapered radiation flares are defined as follows

$$y_{\text{in}} = \begin{cases} \pm\left[w_m - 0.5w_m \exp(C_1 z)\right], & 0 < z < 14.6 \\ \pm\left[C_2 - C_3 \exp(C_4 z - C_5)\right], & 14.6 < z < 33.4 \end{cases}, \quad (1)$$

$$y_{\text{out}} = \begin{cases} \pm\left[0.5w_m \exp(C_6 z)\right], & 0 < z < 2.16 \\ \pm\left[C_7 z - C_8\right], & 2.16 < z < 3.4 \end{cases}, \quad (2)$$

where y_{in} and y_{out} exhibit the distances from the central axis to the inner and outer edges of the tapered radiation flares, respectively. C_j, $j = 1, 2, 3, 4, 5, 6, 7, 8$ are the coefficients to be optimised. Table 1 shows the final optimum values of C_j, $j = 1, 2, 3, 4, 5, 6, 7, 8$ and the geometrical parameters. The profile curve equations in (1) and (2) are obtained through a trial and error method. All of the coefficients and parameters are optimised through extensive simulations and optimisation via Ansoft HFSS. The optimisation goals are set to reach an antenna with a small size and satisfactory radiation characteristics such as good radiation patterns, relatively high gain, and low cross-polarisation over the entire operating bandwidth. It is noticeable that the aforementioned curves have a great effect on the return loss of the designed antenna whereas these curves have little effect on the gain [30, 31]. In order to enhance the gain of the designed AVA while keeping the compact size, the modified AVA as shown in Fig. 1*b*, is proposed. The ends of the tapered radiation patches are rounded to eliminate diffraction from corners. Consequently, as will be seen later, both the gain and directivity are partly improved. The radii of the rounded corners of the inner and outer edges are $r_i = 2.7$ mm and $r_o = 4.1$ mm, respectively.

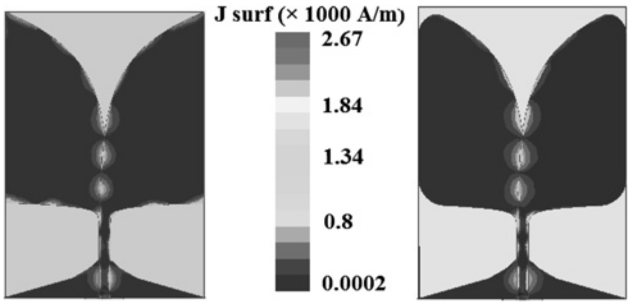

Fig. 2 *Current distribution before and after the rounding at 12 GHz*

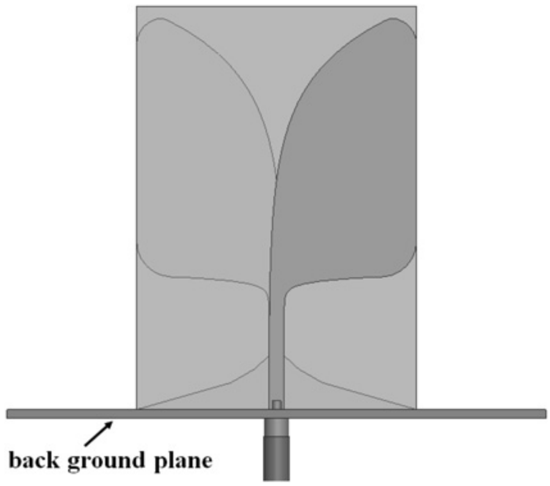

Fig. 3 *Improved AVA with backplane*

The current distributions before and after the rounding at 12 GHz (centre frequency) are presented in Fig. 2. As shown in this figure, although the currents distributed over the open-ends of the Vivaldi antenna have lower magnitudes compared with the currents over other portions, the proposed modification is able to eliminate the unwanted currents over the ends of the radiation patches that radiate with undesirable directions. As a result, the current distribution and maximum radiation gain improve partly by rounding the corners. Besides, to further enhance the antenna gain and front-to-back ratio, a metallic background plane with a size of 50 mm × 60 mm is added to the antenna structure. Although, 1 dB/3 dB gain improvement can be obtained for single/reflector-backed cases, respectively, additional complexity (complicated smooth curve profile, and backed reflector) are needed. So, there is a tradeoff between simplicity of the antenna structure and its radiation performances. However, the reflector-backed Vivaldi antenna is suitable for phased array and radar applications. Fig. 3 shows the improved AVA with backplane. The backplane reflects any radiation going in a direction opposite to that of the required. This would then effectively increase the forward radiation thus contributing to the gain of the antenna.

3 Results and discussion

To verify the simulation results, a prototype of the designed AVA was fabricated, tested, and compared with the simulations. Fig. 4

Table 1 Final optimum values of the coefficients and geometrical parameters

Coefficient/parameter	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	w	l	l_p	l_g	w_m
value	0.047	10.05	6.546	0.05	0.30	0.414	10.87	21.4	31.2 mm	45 mm	30 mm	6.3 mm	1.7 mm

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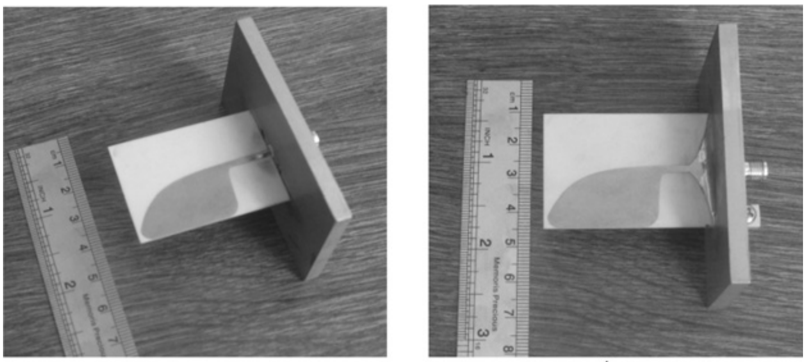

Fig. 4 *Photograph of the fabricated prototype*

a Top view
b Bottom view

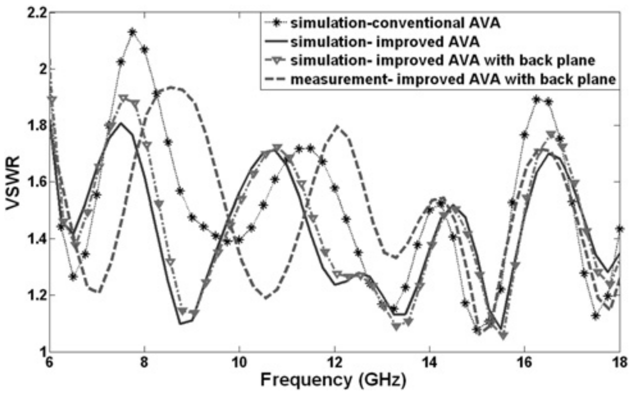

Fig. 5 *VSWR of the designed antennas*

shows the fabricated prototype. The antenna is fed through a 50 Ω SMA connector. Fig. 5 presents the simulated VSWR results of the different antennas. It is seen that the maximum value of the VSWR for conventional AVA is less than 2.2, while the VSWR curves of the improved AVA and improved AVA with background plane are less than 2 over the desired frequency range of 6–18 GHz. Moreover, the measured VSWR of the improved AVA with backplane is also plotted in this figure. The experimental result is in satisfactory agreement with the simulation one.

The simulated *E*-plane (*y–z* plane) and *H*-plane (*x–z* plane) radiation patterns of the three antennas at the centre frequency (12 GHz) are compared in Fig. 6. It can be seen that the considerable difference exists between radiation patterns of the three antennas. A significant improvement of front-to-back ratio and directivity is obviously obtained specifically in the *H*-plane by the modified structure with backplane.

The simulated and measured co- and cross-polar far-field radiation patterns of the improved AVA with backplane at several typical frequencies are presented in Fig. 7. A good agreement is observed, which further verifies the simulation results using Ansoft HFSS. These patterns show that the designed antenna provides linear polarisation with cross-polarisation level at least 20 dB lower than the co-polarisation level. The cross-polarisation levels at other frequencies are also very small, indicating good polarisation purity.

Fig. 8 shows a gain comparison between different antennas. It is obvious that the gains of the improved AVA and improved AVA with backplane are considerably enhanced due to the rounded corners and background plane, respectively. According to the measured result, the antenna peak gain is 8.4 dB and the gain variation within the bandwidth is less than about 1.4 dB. The discrepancy between simulation and measurement is due to the fabrication imperfections, measurement errors, and test equipment's.

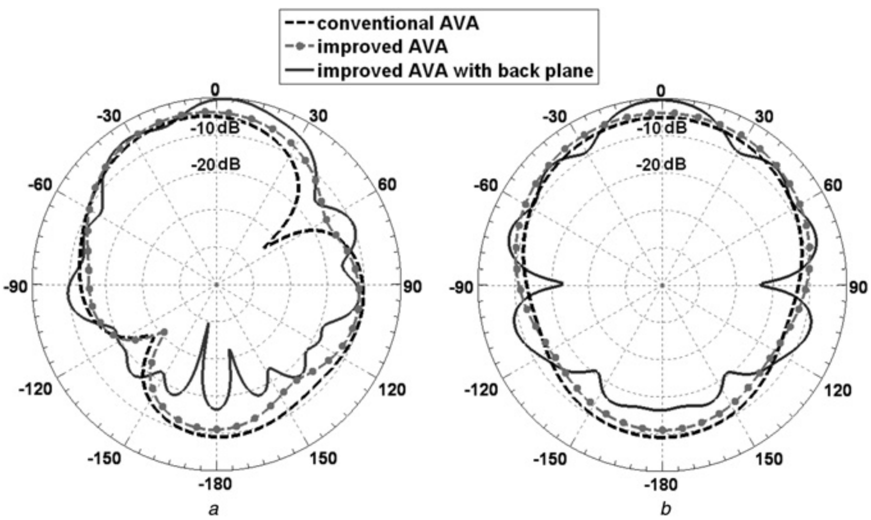

Fig. 6 *Simulated far-field radiation patterns of the deferent antennas at 12 GHz*

a E-plane
b H-plane

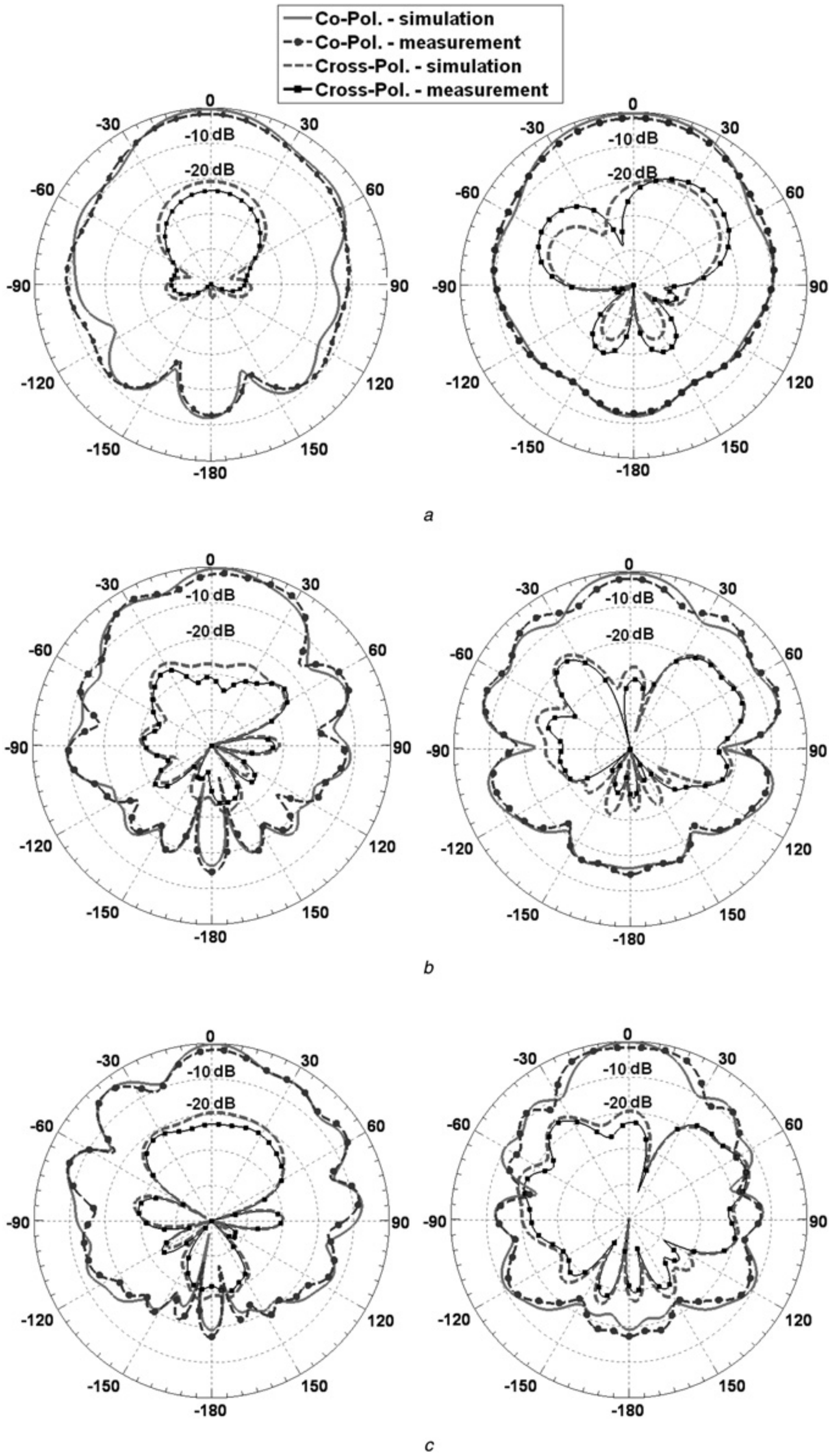

Fig. 7 *Simulated and measured far-field patterns of the improved AVA with backplane (left: E-plan, right: H-plane)*

a At 6 GHz
b At 12 GHz
c At 18 GHz

As was mentioned before, a major drawback of the conventional Vivaldi antennas with bandwidth up to multiple-octave or one-decade is the main beam splitting at high frequencies. This deterioration can be visualised in a three-dimensional (3D) simulated radiation pattern plot. However, the operation bandwidth of the proposed antenna is 3:1, which is much less than one-decade. Therefore, it is expected that the high order dipole modes do not excite and the main beam do not split within such a bandwidth. Fig. 9 illustrates the simulated 3D far-field patterns of the improved AVA with backplane at band edge frequencies. As anticipated it is seen that the designed antenna has desirable characteristics, i.e. it has one dominant main lobe without split in the entire frequency band.

One of the significant parameters in the broadband communication system design is the group delay between transmitting and receiving antennas, which shows the pulse

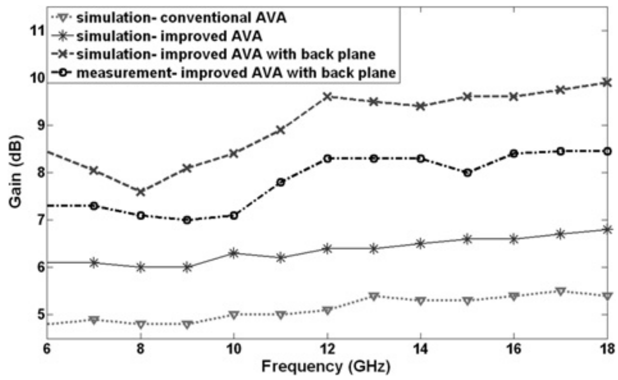

Fig. 8 *Comparison of gain between three antennas*

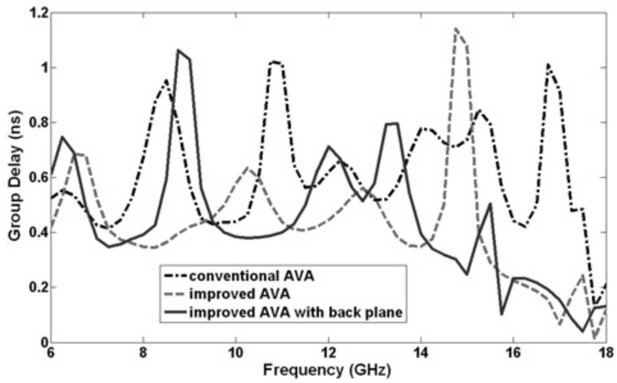

Fig. 10 *Group delay of the designed antennas*

distortion at the receiving antenna. To prevent the pulse distortion, the group delay must be constant. Fig. 10 shows the simulated group delay of the designed antenna. As depicted in this figure, the variation (peak-to-peak deviation) of the group delay for all of the designed antennas is less than 1.1 ns over the entire frequency range, showing proper dispersion performance of the designed antennas. In other words, the result indicates that the modified antenna is reliable so that a transmitted signal will not be seriously distorted by the proposed antenna. The peak-to-peak values of the group delay of the antennas presented in [18, 29, 32] are 1, 4, and 1.5 ns, respectively. Compared with the aforementioned designs, the proposed antenna has an acceptable peak-to-peak value of the group delay. Thus, the modified antenna is suitable for the wideband communication applications.

In comparison with the triplate Vivaldi antenna presented in [10], the main advantage of the designed antenna is its simplicities which avoid the use of further layers of dielectric and metallisation. Moreover, it is noted that in [11], only the simulation results (based on traditional Vivaldi elements) were presented. Also, the operating frequency range in [11] is about 1–6 GHz. While, in this paper, an AVA for the operating frequency range of 6–18 GHz is designed and experimentally studied. Although, in [12], a UWB antenna based on a slot-line feed structure, a bowtie horn, and a rolled edge termination was developed, analysed and measured, however, the designed antenna in this paper has a different structure.

It should be noted that communication and phased array systems that operate in the C, X, and Ku-bands are usually designed using separate antennas for each band. Since it is becoming more and more important to use such systems in one setting, it is desirable to design a single antenna that operates in three frequency bands. This, in turn, requires a wideband antenna that covers the three bands. On the basis of the measured VSWR, radiation patterns, polarisation purity, and gain of the designed antenna, the overall bandwidth is seen to be the same as its impedance bandwidth. Preserving the radiation patterns and excellent polarisation purity are extremely important factors in designing broadband antennas. Many of the existing broadband, single element, Vivaldi antennas achieve broadband operation from two different points of view: impedance matching and radiation pattern, which cannot be achieved together, while the proposed antenna presents good radiation parameters over the C, X, and Ku-bands from 6 to 18 GHz. According to these results, the designed antenna can be useful for broadband communication and phased array applications.

4 Conclusion

A broadband AVA with enhanced radiation characteristics is presented. Both the gain and directivity are improved by rounding the corners of the tapered patches. To further enhance the antenna gain and front-to-back ratio, a metallic background plane is added to the antenna structure. A prototype of the modified antenna is fabricated and experimentally studied. The experimental results are in good agreement with the simulation ones. The designed antenna exhibits satisfactory characteristics such as small size, low cross-polarisation, LVSW ratio, relatively high gain of 7–8.4 dB, almost constant group delay, and stable radiation patterns over the C, X, and Ku-bands from 6 to 18 GHz which make this antenna

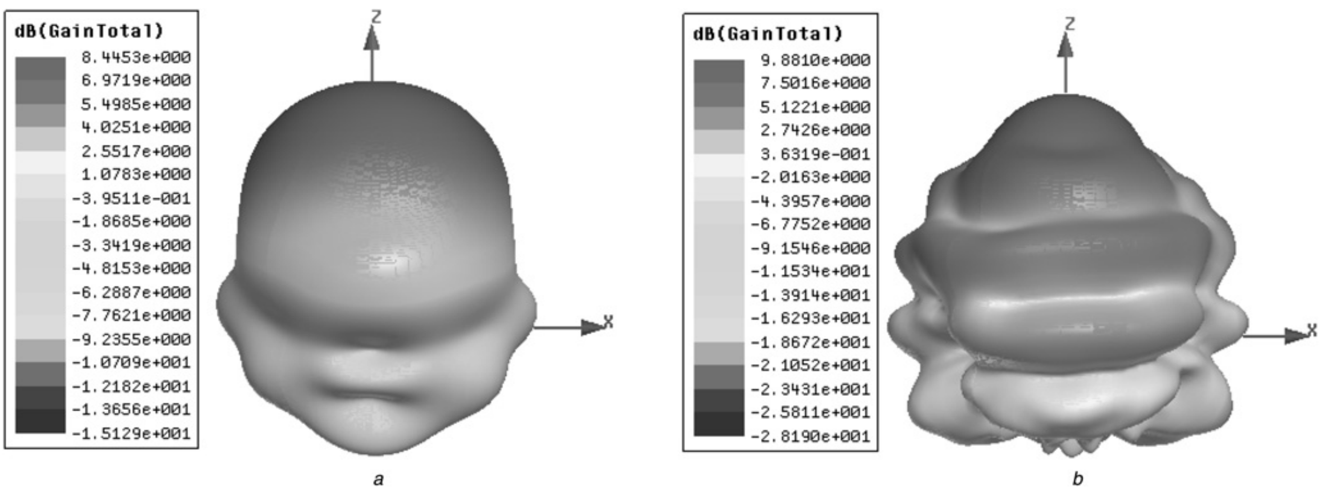

Fig. 9 *3D simulated radiation patterns of the improved AVA with backplane*

a At 6 GHz
b At 18 GHz

suitable for use in broadband communication and phased array applications.

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