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A High-Performance Conformal Antipodal Vivaldi Antenna for Imaging Applications

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Abstract

This paper presents a modified conformal antipodal Vivaldi antenna (AVA) that has been developed to increase its operational bandwidth and enhance its radiation characteristics. The introduction of tilted elliptical slits effectively addresses the lower frequency limitation while also enhancing radiation performance at lower frequencies. Additionally, the antenna incorporates a triangular dielectric lens to boost gain at higher frequencies. To mitigate phase reversal in the aperture of the flares, an elliptical microstrip patch is strategically placed between the flares. The proposed AVA design is rigorously analyzed using HFSS electromagnetic simulation software on a Rogers RO4350B substrate, characterized by a ε_r of 3.55, a loss tangent (tanδ) of 0.0027, and dimensions of 100 × 75.7 × 0.5 mm³. For conformal analysis, the proposed antenna is mounted on a Teflon dielectric cylinder section. This comprehensive design is intended for microwave and millimeter-wave imaging applications, demonstrating superior performance in terms of simulated reflection coefficient, end-fire gain, and radiation pattern across both planar and conformal configurations.

1. Introduction

The stable radiation characteristics, excellent directivity, and ultra-wide bandwidth of the Vivaldi antenna offer significant advantages for high-resolution imaging applications [1-2]. The Vivaldi antenna is highly effective in producing high resolution when used in imaging systems due to its capacity to send and receive wideband signals. These signals are essential for capturing delicate details. The antenna's ability to conform to different surfaces allows it to be put on a wide range of surfaces, making it more useful in a variety of environments, such as security screening, medical diagnostics, and industrial inspection. The Vivaldi antenna is an essential component for creating advanced imaging systems that need accurate and comprehensive representations of scanned objects or areas. Its adaptability, high gain, and precise phase correction capabilities make it crucial for this purpose [3].

The exponentially tapered slot antenna, often known as the Vivaldi antenna, was first introduced by Gibson in 1979. This antenna is distinguished by its low profile, straightforward design, and the ability to operate at ultra-wideband frequencies [4]. On the other hand, it suffers from radiation loss at higher frequencies. Gazit changed the original design in 1988 to create the AVA, which contains two exponential flares on either side of the substrate to increase bandwidth and radiation performance [5]. This decision was made in response to the fact that the original design had been modified. When conformed to a surface at both lower and higher frequencies, the AVA has problems such as gain instability and skewed radiation patterns. These problems occur despite the fact that these upgrades have been implemented.

Several studies have focused on enhancing the efficiency of conformal antennas. For example, a conformal antenna with a conical dielectric surface operates within the operational bandwidth of 2-12 GHz. However, it exhibits altered radiation patterns when used at higher frequencies [6]. A different conformal antenna, when mounted on a conducting cylinder, exhibits favorable radiation properties but possesses a high cut-off frequency [7]. In addition, a proposed AVA has a corrugated edge, director, and meta-material, but it has significant dimensions [8-9]. A stepped connection arrangement is utilized in [10] to improve the impedance bandwidth between the slotline and tapered patches. Linearly tapered slot antennas employ unequal half-circular slots to enhance antenna gain [11]. The paper discusses AVA that have circular-shaped loads and tapered slot edges. These modifications aim to expand the lower frequency range in which the antennas may operate. The specific designs are described in references [12] and [13]. Nevertheless, these antennas frequently demonstrate diminished amplification throughout the entire range or particularly at lower frequencies [10-13].

This work aims to present an enhanced planar antipodal Vivaldi antenna design that achieves optimal impedance matching in the frequency range of 2.5-30 GHz, while also delivering a gain of 5-13 dBi. In order to evaluate the conformal properties, the suggested planar antenna was mounted onto a Teflon dielectric cylinder section, which had a surface tilt angle of 5-10°. The conformal AVA exhibits a frequency range of 2.5-30 GHz and a gain of 4-10 dBi. It also demonstrates advantageous unidirectional radiation characteristics in the end-fire direction.

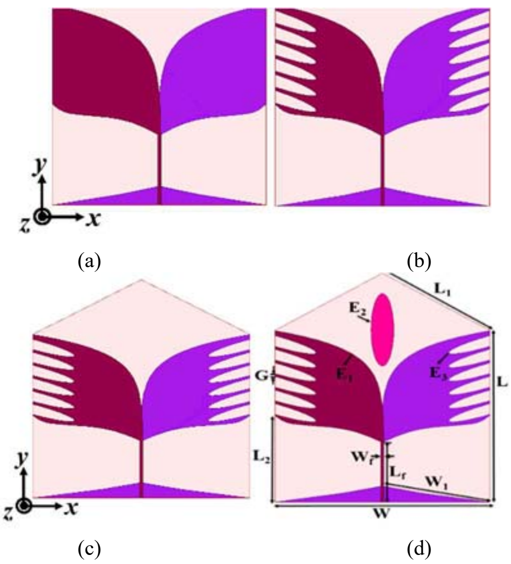


Figure 1. Evolution stages of Proposed Antenna (a) AVA (b) AVA-ES (c) AVA-ES-DL (d) AVA-ES-DL-EP.

Table I. Optimized Antenna Dimensions

Parameter	Dimension (mm)	Parameter	Dimension (mm)
L	75.75	W_f	1.1
W	75.7	L_f	26
L_1	45.5	G	1.22
L_2	38.2	W_1	37.96

2. Antenna Design and Evolution

A. Planar analysis of proposed design:

As shown in Fig. 1, the design of an AVA combines two exponential flares on both sides of the substrate, which together form a tapered slot. Additionally, the AVA incorporates elements such as elliptical slits (ES), a triangular dielectric lens (DL), and an elliptical patch (EP). The purpose of the bottom flare is to act as a ground plane and facilitate the transition from a microstrip line to a parallel stripline. It is equipped with a triangular taper. As can be seen in Fig. 2(a), the simulated reflection coefficient of the AVA covers a frequency range that extends from 3 to 30 GHz. Additionally, the gain in the end-fire direction varies from 5-9 dBi throughout all of the respective operating bandwidth. The AVA is improved by incorporating symmetrical elliptical openings at both edges, known as AVA-ES, as seen in Fig. 1(b). The elliptical slits modify the flow of current, addressing the drawbacks of the exponential slot on the current path and decreasing the low cut-off frequency from 3 GHz to 2.5 GHz, as shown in Fig. 2(a). The substrate form is additionally altered by incorporating a triangle dielectric lens (DL), referred to as AVA-ES-DL, as depicted in Fig. 1(c). This modification results in a gain enhancement of 2 dBi at higher frequencies. In addition, an elliptical patch that acts as a parasite is inserted into the entrance of the antenna, together with the elliptical slits and dielectric lens. This configuration is referred to as

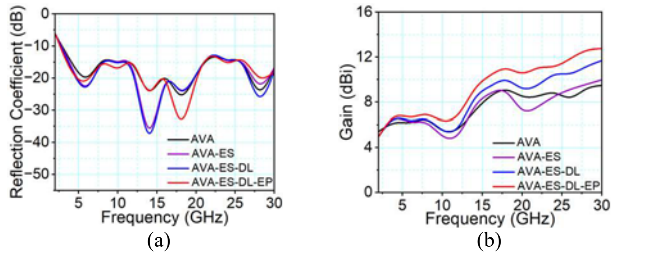
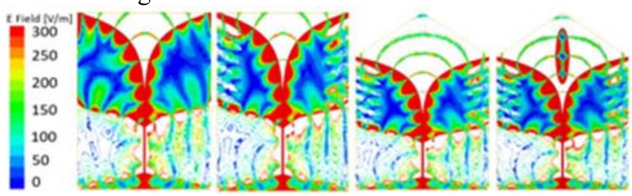


Figure 2. (a)Simulated Reflection coefficient and (b) Gain of different configurations of the modified AVA.



(a) AVA (b) AVA-ES (c) AVA-ES-DL (d) AVA-ES-DL-EP

Figure 3. Electric-field distribution of various modified AVA at 14 GHz

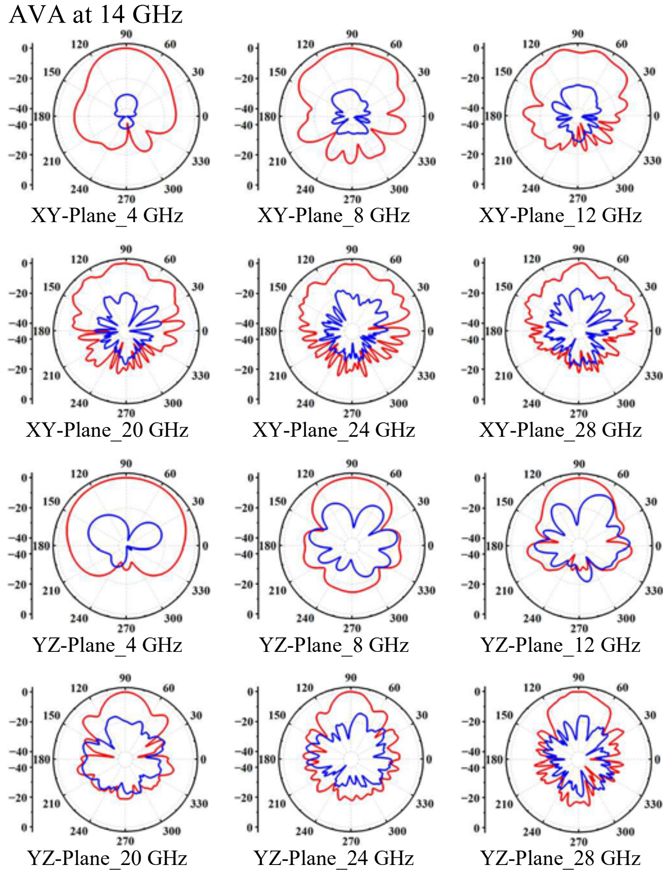


Figure 4. Normalized radiation pattern of proposed planar antipodal Vivaldi antenna**.**

AVA-ES-DL-EP, as shown in Fig. 1(d). This arrangement guarantees a consistent distribution of electric current at higher frequencies, leading to a steady emission pattern and an increase in gain ranging from 5-13 dBi throughout the range of frequencies it operates in. The exponential flare E1, elliptical patch E2, and elliptical slits E3 are designed using Eqs . (1), (2), and (3), respectively. The precise measurements of the proposed antenna arrangement are presented in Table I. The antenna is modelled using a Rogers 4350B substrate, which has a thickness of 0.508 mm.

$$y = c1 \times e^{ax} + c2 \tag{1}$$

Where, a = *0.0785, c1 = 0.3, c2 = 0.55*

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{2}$$

Where, *a = 4, b = 16*

$$\frac{x^2}{m^2} + \frac{y^2}{n^2} = 1 \tag{3}$$

Where, *m = 2.5, n = 10*

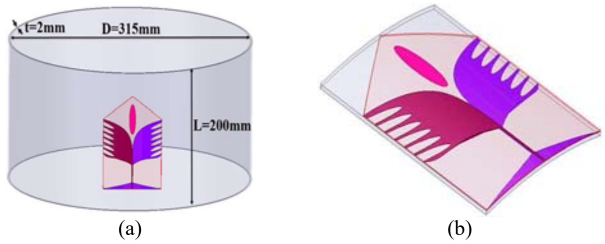
Fig. 3 illustrates the electric-field distributions at 14 GHz for various stages of the planar-modified AVA. These depictions highlight the changes in radiation characteristics, effectively demonstrating the radiation properties across different stages of modification. The presence of elliptical slits effectively decreases the amount of fringe field energy around the edges and prevents the occurrence of edge currents. The redesigned substrate, which has a triangle form, acts as a dielectric lens, guiding the electromagnetic waves in the end-fire. Additionally, the elliptical patch enhances the field coupling between the tapered slot and the radiation patterns through the generation of constructive interference.

Fig. 4 exhibits the normalized radiation pattern of the AVA-ES-DL-EP in both the E-plane (XY-plane) and H-plane (YZ-plane) at six distinct frequencies within the operational range. With an increase in frequency, the radiation pattern becomes more concentrated, resulting in a fall in the half-power beamwidth from 45° to 70°. When the antenna is pointed in the end-fire direction, it shows a well-defined radiation pattern that only goes in one direction. There is also a noticeable difference between the co-polarized and cross-polarized radiation patterns in either plane.

B. Conformal analysis of proposed design:

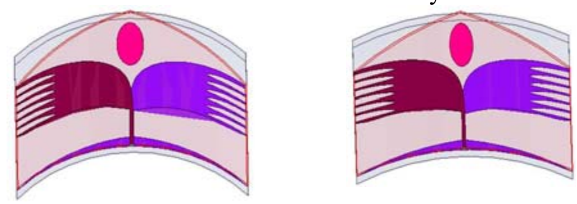
The proposed AVA is conformed on a Teflon dielectric cylindrical section having a dielectric constant of 2.1 with a thickness of 2 mm and a diameter of 315 mm. A proposed modified AVA conformed to the cylindrical section is shown in Fig. 5(a). The 3D view of the antenna, which is part of the conformal setup mounted on a cylindrical section, is simulated and analyzed, as depicted in Fig. 5(b). The antenna is mounted on cylindrical surfaces with different curvatures to investigate the conformal characteristics at different surface angles.

Fig. 6 depicts the antenna positioned on dielectric cylindrical surfaces with diameters of D1=100 mm, D2=200 mm, and D3=315 mm. The length of the cylinders is kept constant at 102 mm, with a thickness of 2 mm. Additionally, all three cylinders have a dielectric constant of 2.1. Fig. 7 displays the simulated reflection coefficient and gain of the conformal antenna with different cylindrical curvatures. The findings suggest that when the curvature intensifies, both the reflection coefficient and gain deteriorate at higher frequencies. The degradation is caused by the supplementary electric field produced in the negative Z-axis direction, which deteriorates



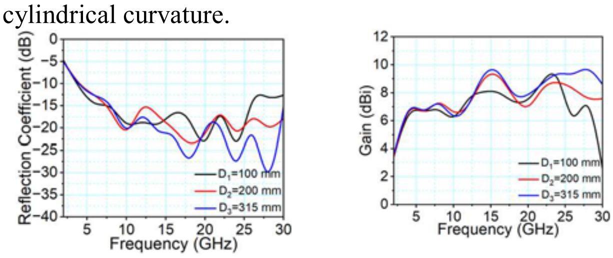
(a) (b)

Figure 5. a) The planar modified antipodal Vivaldi antenna conformed on Teflon dielectric cylinder (b) 3D- View of a section of conformed modified AVA on a cylindrical section.



(a) D_1=100 mm (b) D_2=200 mm

Figure 6. Modified AVA conformed on different cylindrical curvature.



(a) (b)

Figure 7. (a)Simulated Reflection coefficient and (b) Gain of the different antenna curvature on cylindrical dielectric section

Table II. Comparative analysis of proposed antenna with literature

Ref.	Ant. size (mm^3)	Substrate-Dielectric constant	Peak Realized Gain (dBi)	Oper. Bandwidth (GHz)	Conformal Cha.
[6]	116×124×0.5	Teflon-F4B-3.5	10	2-12	Yes
[8]	260×120×0.762	N.R.-3	14.4	1-28	No
[9]	40×90×0.508	RO4003C-3.38	14	3.4-40	No
[10]	116×124×0.5	Rogers 4350B-3.5	12	2-12	Yes
[*]	**100×75.7×0.5**	**Rogers 4350B-3.5**	**13**	**2.5-30**	**Yes**

[*]-Proposed antenna, Ant.- Antenna, Cha.-Characteristics, Oper.-Operational

the antenna characteristics. Fig. 8 displays the simulated normalized radiation pattern of the conformal modified AVA in the E-plane (XY-plane) and H-plane (YZ-plane) at four distinct frequencies within the operational bandwidth. The radiation patterns exhibit consistent unidirectional radiation in the end-fire. The cylindrical curvature of the conformed modified AVA results in the generation of an extra electric

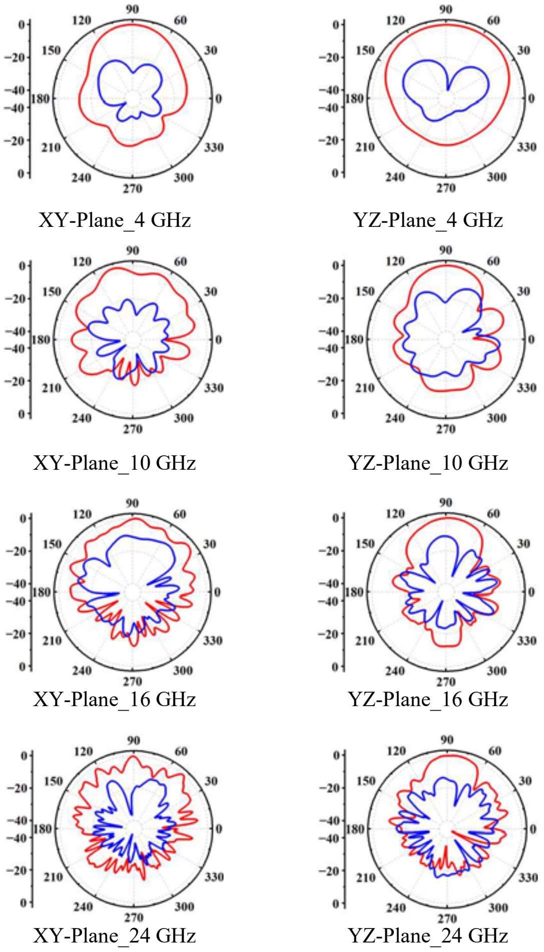


Figure 8. Normalized radiation patterns of proposed conformal modified AVA at D3 = 315 mm.

field component in the negative Z-axis direction, which leads to a slight increase in the levels of cross-polarization.

Table II presents a comprehensive comparison between the performance of the proposed improved AVA and other current designs. The comparison takes into account several aspects like antenna size, substrate material, peak realized gain, operational bandwidth, and conformal properties. Table II clearly shows that the proposed modification to the AVA geometry introduced here outperforms other antennas described in the literature in terms of impedance matching, gain, and radiation pattern.

3. Conclusion

This paper introduces an ultra-wideband modified AVA operating across a broad frequency bandwidth of 2.5 GHz to 30 GHz. The antenna demonstrates exceptional impedance matching and achieves a high realized gain of 13 dBi in the end-fire direction. It maintains a consistent radiation pattern with minimal side lobe levels, ensuring stable performance. Conformal analysis confirms robustness, showing minimal degradation at higher frequencies. An in-depth investigation into the effects of cylindrical curvature for conformal analysis reveals that the ultra-wideband and stable unidirectional characteristics are preserved. These findings indicate the suitability of the proposed modified AVA for various applications, particularly in microwave and millimeter-wave imaging. Its combination of wide operational bandwidth, high gain, and stable radiation pattern makes it an excellent candidate for advanced imaging systems and other high-frequency applications.

4. References

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