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Study of Construction Techniques Applied to the Vivaldi Antipodal Antenna

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ABSTRACT

This article examines the evolution and construction techniques of the Vivaldi antipodal antenna (AVA), a broadband antenna utilized in a range of applications, including microwave medical imaging systems (MMIS), radars, and 5G communications. The article examines the operational characteristics of the AVA and the impact of substrate dielectric properties on its performance, as well as analyzes various construction techniques employed in the development of the AVA, including the use of directors, dielectric lenses, and metamaterials, antenna arrangements, and resonant and radiating cavities. It elucidates the advantages and disadvantages inherent to each approach.

1. INTRODUCTION

Antennas are one of the most important elements of a microwave medical imaging system (MMIS). It should be noted that Vivaldi Antipodal Antennas (AVA) are used in UWB systems due to their low cost, compact profile and dimensions, ease of integration with systems [1], [2] and they also stand out for their wide applicability in MMIS [3], [4], [5], [6], [7], Radars [2], [8], [9], high-power missiles, unmanned aerial vehicles [1], 5G communications [10], [11], remote sensing [2], [12], locating objects through obstacles [13], signal jammers [14], sterilizing microorganisms such as fungi, viruses, and bacteria [15], analyzing concrete structures [11], and satellites [1], [9].

The AVA was developed by Gazit in 1988 to improve some aspects of the operation of Gibson's Vivaldi antenna, which is coplanar (AV - 1979) [16]. One of the improvement aspects was the height reduction of the rear lobes (RLL) compared to the AV [16]. Over time, design techniques have been applied to conventional AVA to improve directivity, gain, reduction of strabismus, side lobe level (SLL), and cross-polarization. In this work, the techniques studied were Balanced AVA (BAVA) with and without director [9], AVA with director in the main radiator [2], dielectric and metamaterial lenses [17], PLA (polylactic acid) lenses [15], [18], tapered slot edge (TSE) [9] and regular slot edge (RSE) [12], [12] and regular slot edge (RSE) lateral resonant cavities [9], [14] and the exponential slot edge (ESE) [9] and fractal slot edge (FSE) radiating cavities [3], [5], [7].

Over time, new techniques have been studied and applied to conventional AVAs to improve the operating parameters to meet the requirements of microwave systems. These techniques have been studied to develop this work and will be discussed below.

This work is divided into sections: Section 2 presents the constructive theory of the conventional AVA together with the effects of radiation caused by the dielectric constant of the substrates, Section 3 presents the techniques studied that have been applied to the conventional AVA, and Section 4 presents the conclusion of the study of the techniques.

2. VIVALDI ANTENNA THEORY

The AV, developed by Gibson in 1979, is a coplanar antenna [8] that lies in a single plane of the substrate and is fed by a balun that does not depend on frequency because it theoretically has unlimited bandwidth, has linear polarization, the gain is proportional to the total length of the electromagnetic (EM) waves, and the rate of change is the energy flowing in the AV [19].

The equation used for the antenna's main exponential radiator (MEAR) curve is $y = \pm A_y e^{Px}$, where A_y is the point on the y-axis where the MEAR curves intersect. Therefore, the center of the aperture P is the aperture rate for a given width of the MEAR and x is the total length of the MEAR [19].

Figure 1 shows an AV with the MEAR at the top and the balun at the bottom. The Cartesian coordinates are inserted to make it easier to understand the equation used to project the curves of the AV.

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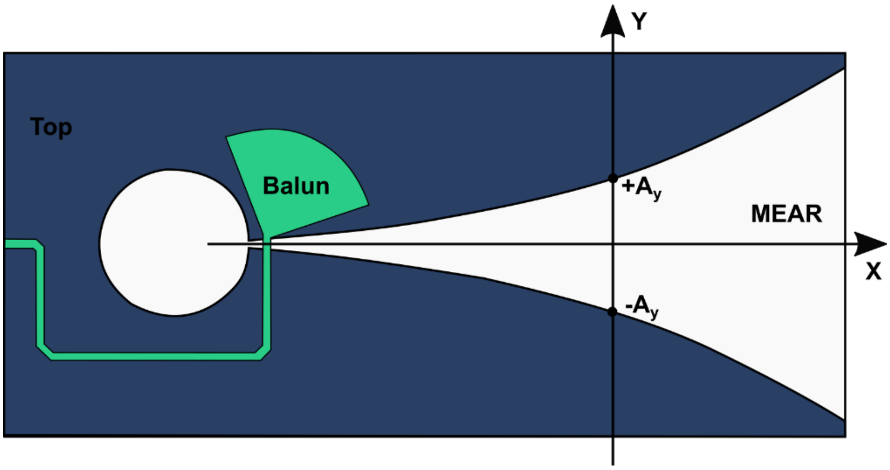

Figure 1. Elements of the Vivaldi coplanar antenna structure.

The balun, used to feed the AV, has a complex design [5]. The fan-shaped stub introduces a loss that even distorts the radiation patterns when the AV is operating at high frequencies. Additionally, the long, sharp edges of the stub generate diffraction of the MS and reduce the gain.

The AVA, developed by Gazit (1988), exhibits superior operational characteristics compared to the AV. It preserves the AV's exponential MEAR curves, reduces the length of the lateral edges, and the tips of the curves (previously sharp) become rounder, thereby enhancing bandwidth [13], directivity [9], beam symmetry in the E (electrical) and H (magnetic) planes [12], efficiency [20], and reducing RLL [16].

AVAs operate on the progressive wave principle, whereby electromagnetic energy is gradually radiated as it traverses the antenna structure. The MEAR shape, also referred to as the "flare," enables the gradual transfer of energy from the feed line into free space, resulting in a broad bandwidth. The AVA directs the flow of electromagnetic energy toward the antenna aperture, thereby maximizing radiation and directivity. **Figure 2** illustrates an AVA demonstrating the micro transmission line (MTL) responsible for the feed and impedance matching between the feed connector and the MEAR, as well as the exponential radiator which acts in impedance matching with the MS propagation medium.

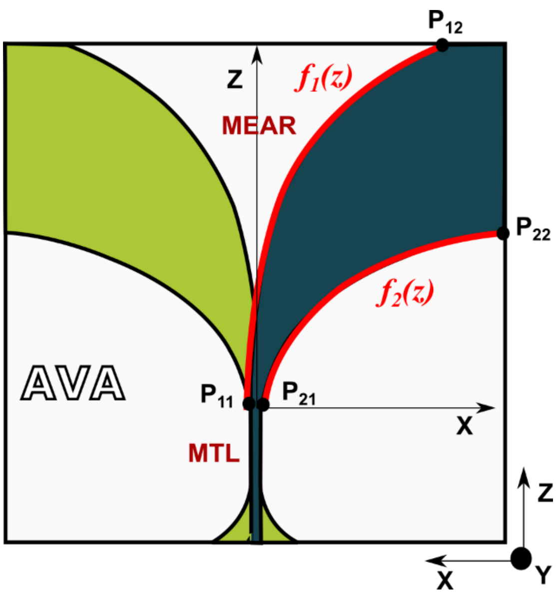

Figure 2. Conventional Antipodal Vivaldi Antenna.

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The opening of the MEAR is projected by the exponential functions $f_1(z)$ which originate at point P_{11} and conclude at P_{12}, and $f_2(z)$, which originate at points P_{21} and P_{22}. These functions can be obtained from Equation (1).

$$f(z) = c_1 e^{Rz} + c_2 \tag{1}$$

Therefore, R represents the opening rate of the exponential, while c_1 and c_2 are the curves that can be derived from Equations (2) and (3), respectively.

$$c_1 = \frac{x_2 - x_1}{e^{Rz_2} - e^{Rz_1}} \tag{2}$$

$$c_2 = \frac{x_2 e^{Rz_2} - x_1 e^{Rz_1}}{e^{Rz_2} - e^{Rz_1}} \tag{3}$$

The aforementioned equations facilitate the design of AVAs with varying MEAR openings and edge configurations, as evidenced by the work of [20].

2.1. Impacts of the substrate

The dielectric characteristics of the substrate and MTLs contribute to the resilience of antennas against radiation. Impedance matching is a requisite measure to reduce losses due to standing waves between the MTL and the antenna. The dielectric characteristics of substrates exert a significant influence on the efficiency, bandwidth, dimensions, and gain of antennas. A high dielectric constant (ε) results in greater confinement of electromagnetic fields within the substrate, which in turn reduces gain, bandwidth, and undesirable coupling. Additionally, these characteristics make them ideal for use in security systems due to their narrow bandwidth. In contrast, antennas with low ε exhibit increased gain, bandwidth, and physical dimensions, as well as more detached electromagnetic fields, which facilitate radiation [1].

In the study conducted by [21], antennas with lateral cavities were developed using Hilbert fractals with three distinct dielectric constants: 2.0, 4.3, and 6.6. The aforementioned antennas were designated HC2.0-FSE-AVA, HC4.3-FSE-AVA, and HC6.6-FSE-AVA, in that order. **Figure 3** illustrates the return loss of each antenna and that of the conventional AVA, which employed a 4.3 substrate. This demonstrates the expansion and contraction in the bandwidth of the antennas in accordance with ε.

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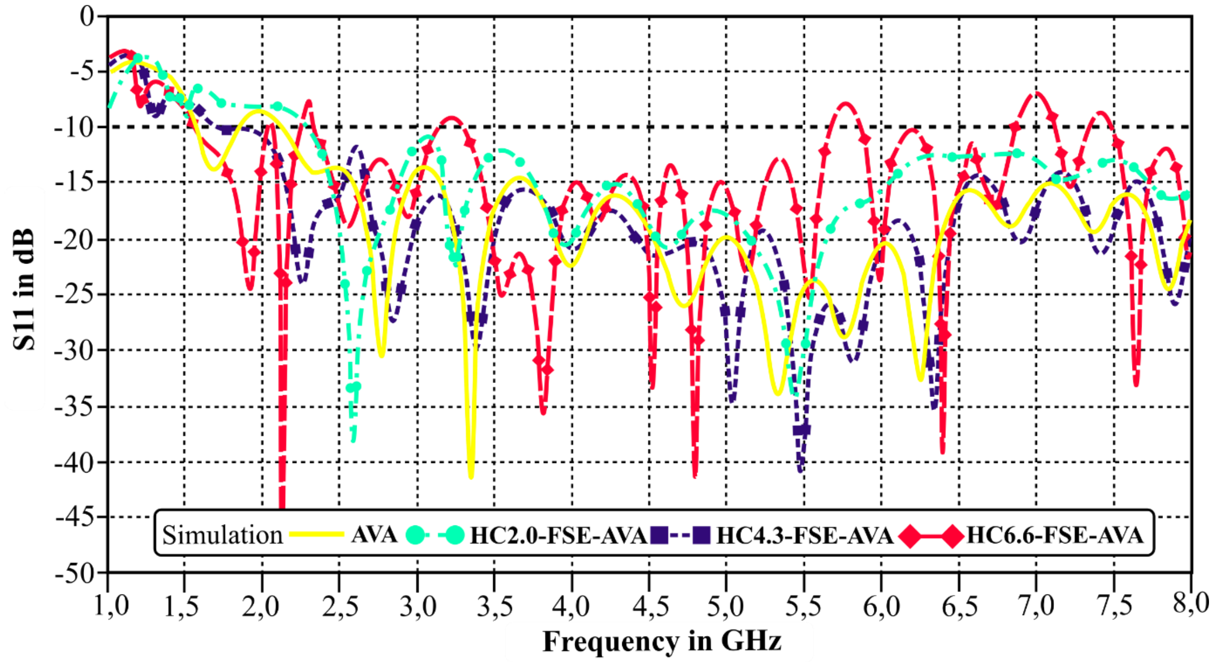

Figure 3. Return loss parameter (S11) of antennas with dielectric constants of 2.0, 4.3, and 6.6 [21].

Figure 4, also derived from the work of [21], illustrates the gains in relation to frequency and the impact of varying dielectric constants on the gain performance of the antennas, thereby substantiating the assertion put forth by [1].

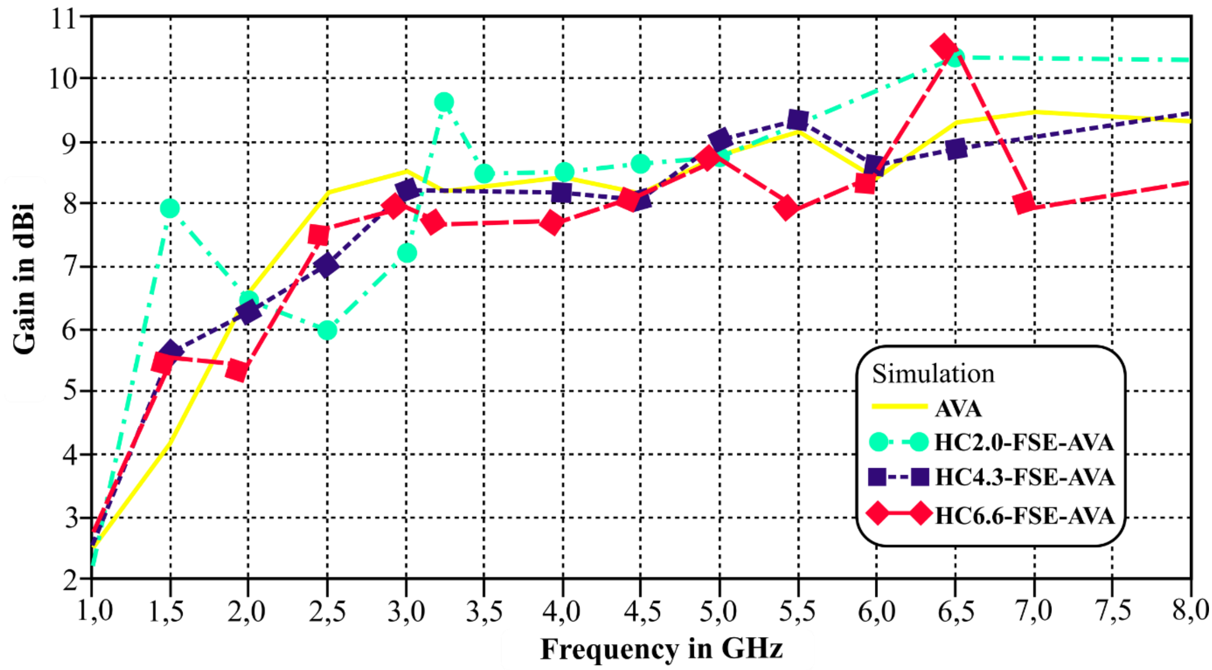

Figure 4. Depicts the gain of antennas with dielectric constants equal to 2.0, 4.3, and 6.6 [21].

The thickness of the substrate also exerts an influence on the phase changes of the wave radiated by the antenna, which can give rise to distortions and an increase in cross-polarization when subjected to high frequencies. It is therefore recommended that a substrate with a low dielectric constant and a thin thickness be used.

3. AVA CONSTRUCTION TECHNIQUES

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3.1. BAVA - Balanced Antipodal Vivaldi Antenna

BAVA is a balanced AVA that may or may not employ a director, as evidenced by the work referenced in [6]. This technique comprises three substrate layers: two at the extremities where the reference are situated and an inner conductive element. Additionally, there are two outer substrates, as illustrated in **Figure 5**. The aforementioned layers serve to balance the dielectric charge between the conductor and the reference. When a director is present, its function is to act as a waveguide, directing the energy in a centralized manner toward the radiator. This method has the advantage of reducing cross-polarization, strabismus, and improving gain; however, it is more complex to construct and supply, and more expensive than a conventional AVA, as it uses several layers of substrates.

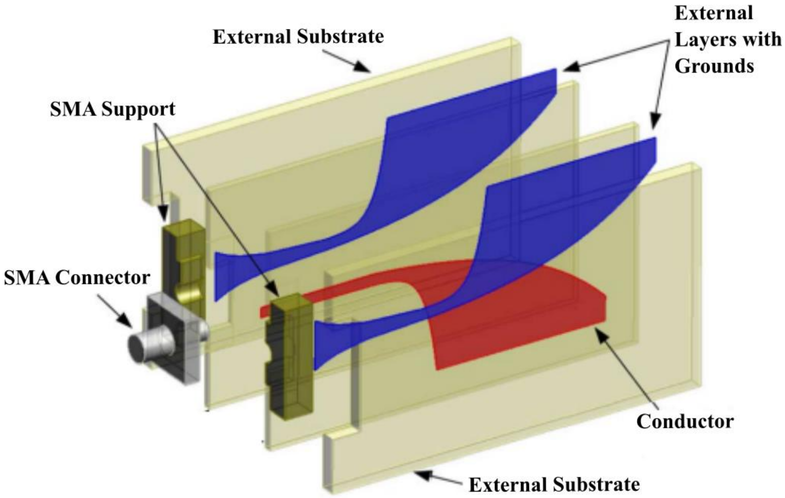

Figure 5. Depicts a Balanced AVA (BAVA) [6].

3.2. Vivaldi Antipodal Antenna with Director

The AVA with an elliptical director (2), situated at the core of the MEAR (**Figure 6**), functions as a waveguide, directing energy toward the center of the MEAR. Additionally, it reduces the phase velocity of electromagnetic waves in relation to the MEAR (6), enhances the gain (17), expands the bandwidth, and improves directivity in comparison to the conventional AVA (2). However, the dimensions of the antenna deviate from the expected norms, with the AVA exhibiting a larger director than the conventional one, as illustrated in **Figure 6** [20].

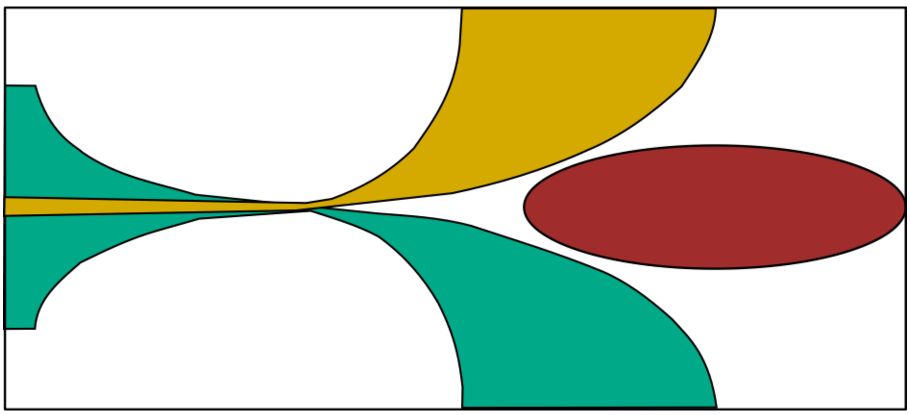

Figure 6. Illustrates the application of the ellipsoid director technique in the AVA [2].

3.3. Vivaldi Antipodal Antenna with Lenses

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The technique employing dielectric lenses crafted from metamaterials [2], [18] and polylactic acid (PLA) [16], [18] yields enhanced directivity, gain, diminished SLL [14], [15], [17], [20], and augmented radiation stability across the entire bandwidth [14]. Notably, this approach allows for the realization of a system with no size limitations while maintaining the antenna's original physical dimensions. **Figure 7** depicts a Palm Tree class AVA with a PLA filament lens, which was developed via additive manufacturing by [15].

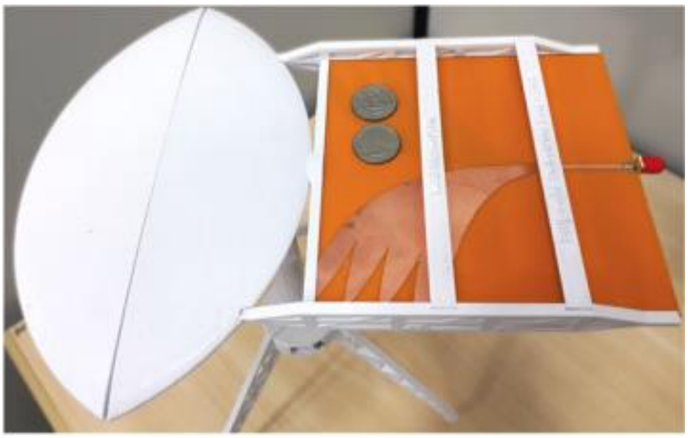

Figure 7. Depicts a Palm Tree class AVA with a PLA filament lens [15].

3.4. Vivaldi Antipodal Antenna Array

Additionally, an antenna array may be employed as a technique. This technique employs a configuration of multiple antennas, as illustrated in **Figure 8** of the referenced work by [17], who demonstrated its efficacy in 5G communication. This procedure increases the gain, bandwidth, and SLL of the antenna array, provided that the antennas are arranged in closer proximity to one another. Another issue is the potential for high coupling along this route, which could result in notable reductions in bandwidth and gain, as previously observed by [17]. Furthermore, the complexity of feeding due to impedance matching and larger physical dimensions [20] must be considered.

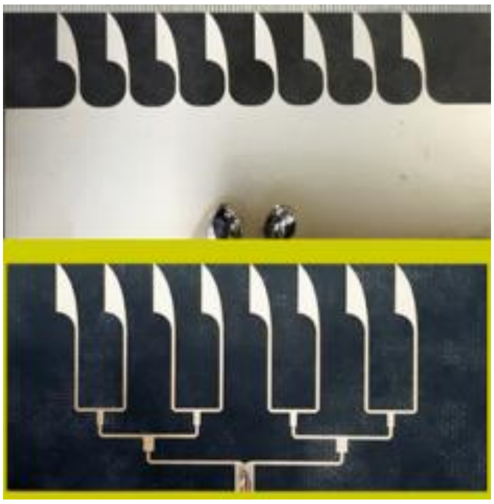

Figure 8. Depicts the AVA arrangement [17].

3.5. Vivaldi Antipodal Antenna with Resonant Cavities

Another form examined in this study was one of the resonant lateral cavities, or slots. These include the RSE, which are rectangular cavities, and the TSE, which are triangular. This method has been demonstrated to result in a reduction in SLL, an alteration in operating

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frequency, an improvement in directivity, and an increase in antenna co-polarization. These resonant slots increase the electrical length while simultaneously reducing the physical size, thereby enabling the generation of inductance and capacitance within the antennas [11]. Accordingly, the RSE operates as an equivalent RLC resonator circuit [12], and, like the TSE, confines the electric fields within its cavities, resulting in a reduction in efficiency [9], [12]. **Figure 9** depicts the RSE model in (a) and the TSE model in (b), as developed in the referenced work [12].

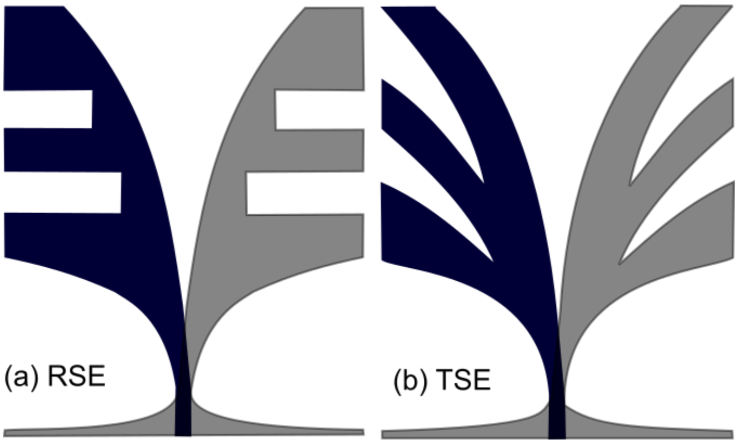

Figure 9. Illustrates the Resonant Cavity Technique, comprising the RSE and TSE [12].

3.6. Vivaldi Antipodal Antenna with Radiating Cavities

In addition to the aforementioned techniques, radiating cavities designated as ESE [9]—which employ exponential curves—and Fractal Slot Edge (FSE) [3], [5], [8], are also utilized. Fractal geometries are employed in this configuration, wherein the cavities serve as parasitic antennas. This configuration controls the currents from the edges of the AVA and channels them to the main radiator, resulting in a simultaneos reduction in SLL and an increase in gain.

Figure 10(a) depicts the ESE-AVA, designated as the "Palm Tree," as detailed in the referenced work [9]. In (b), the antenna with the FSE technique, designated as CNG-FSE-AVA, employs Cantor's neo-Gothic fractal, as referenced by [7].

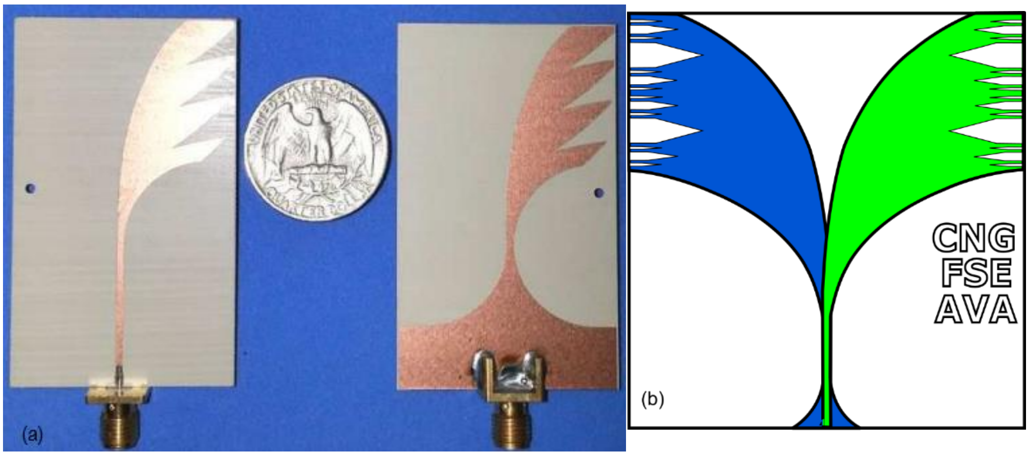

Figure 10. Illustrates two radiating cavity techniques: (a) ESE-AVA [9] and (b) CNG-FSE-AVA [7].

Table 1 provides a summary of the techniques studied, accompanied by an analysis of their respective advantages and disadvantages.

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Table 1. Outlines the advantages and disadvantages of the techniques employed in the context of virtual learning environments (VLEs).

AVA techniques	Advantages	Disadvantages
BAVA	Reduces cross-polarization; Improves gain; Reduces strabismus. Melhora ganho;	Constructive complexity; Complexity in feeding; Higher production costs.
AVA with Director	Improves gain; Improves directivity; Increases bandwidth.	De-characterizes physical dimensions.
Dielectric Lenses, Metamaterials and PLA	Improves gain; Improves directivity; Decreases SLL; Improves radiation stability. Increases bandwidth.	Constructive complexity; De-characterizes physical dimensions.
AVA Array	Improves gain; Increases bandwidth.	Increases SLL level; High coupling; Feeding complexity.
Resonant Cavities (RSE and TSE)	Improves directivity; Reduces operating frequency; Improves copolarization; Reduces SLL.	Decreased efficiency.
Radiating Cavities (ESE and FSE)	Improves directivity; Improves gain; Reduces SLL; Reduces strabismus; Does not decharacterize dimensions.	Complexity of implementing fractals.

4. CONCLUSION

The study of the Antipodal Vivaldi Antenna (AVA) demonstrates progressive advancements in antenna design and performance through the implementation of innovative construction techniques. The principal benefits observed with the implementation of novel techniques included:

a) Enhanced performance: It has been demonstrated that the integration of elliptical directors and resonant cavities enhances the gain, bandwidth, and directivity of the AVA in comparison to the conventional AVA. This enhancement can be utilized in applications that necessitate high efficiency and performance, such as microwave systems and ultra-wideband communications.

b) Impact of the substrate: The selection of a suitable substrate material can have a considerable impact on the performance of an antenna. The study underscores the impact of varying dielectric constants on bandwidth and gain, underscoring the significance of substrate selection in antenna design.

c) Use Fractals: The fractal technique yields enhanced performance relative to the conventional approach, despite the latter's intricate geometry. However, the fractal geometry is highly efficient in terms of spatial occupation, without compromising the dimensions of the AVA.

In conclusion, the advancements in AVA design not only enhance its operational capabilities but also pave the way for new avenues of research and application in communication systems, particularly in the field of medical imaging for pre-diagnosis. The findings underscore the

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significance of sustained innovation in antenna technology to meet the evolving demands of diverse fields of knowledge.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

7. AUTHOR'S CONSTRIBUTION

Raimundo Eider Figueredo: Conceptualization, Methodology, Writing Original Draft, Investigation; Nurhayati Nurhayati: Formal Analysis, Writing Original Draft, Supervision; João Francisco Justo: Data Curation, Review & Editing, Investigation; Alexandre Maniçoba de Oliveira: Software Review & Editing, Investigation.

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