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(Received 10 December 2025, Accepted 2 March 2026, Scheduled 9 April 2026)

Design of Ultra-Wideband Vivaldi Antenna with Enhanced Gain Performance

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ABSTRACT: An enhanced Vivaldi antenna operating in the ultra-wideband (UWB) region—featuring circular slots and a trapezium-shaped parasitic patch Vivaldi antenna (CSTPP-VA)—is presented in this article. The uniformly arranged slots contribute to a wide bandwidth, while the trapezoidal parasitic patch, located in the end-fire region, enhances impedance bandwidth and improves overall antenna gain. The CSTPP-VA operates over the 3.2–11 GHz frequency range with a peak gain of 9 dB. Compared to the conventional coplanar Vivaldi antenna, it exhibits a 3.6 dB gain improvement, demonstrating enhanced radiation performance.

1. INTRODUCTION

Ultra-wideband (UWB) technology has gained significant popularity in modern wireless communication systems due to its high data transmission rates and low power consumption. To support UWB capabilities while meeting the growing demand for miniaturization, improved efficiency, and enhanced performance, the development of advanced antenna designs is essential. With the increasing use of UWB technology in wireless sensor networks, medical imaging, automotive radar, and Internet of Things (IoT) devices, it is crucial to develop efficient, compact, and cost-effective UWB antennas [1, 2]. The Vivaldi antenna, being an end-fire tapered slot antenna, is well known for its wide bandwidth and high directivity. It has been widely used in radar, sensing, and UWB applications.

To enhance the radiation performance of antennas, extensive research has been conducted, exploring various design modifications. A commonly adopted approach involves etching slots of different shapes, such as rectangular, tapered, and graded elliptical ones onto the radiating patch, which significantly improves antenna efficiency and performance. An elliptical pseudo-element has been added with irregularly spaced notches to a tapered slot antenna [3] to decrease side-lobe radiation and improve the directivity of the antenna. A Vivaldi antenna designed using the Cascaded Cavity-Based Substrate Cut-Out (CCSC) technique [4] optimizes low-frequency gain in a compact design while also enhancing high-frequency gain. Various enhancement techniques [5] have been explored to improve antenna gain and radiation characteristics. A balanced antipodal Vivaldi antenna with shaped dielectric lenses [6] improves both gain and bandwidth. Another design integrates an elliptical-shaped director and metamaterials [7] to enhance performance. A Vivaldi antenna utilizing a hyperbolic meta surface [8] is developed to improve antenna isolation. A UWB antipodal Vivaldi antenna with an exponential taper and triangular slots is designed to enhance gain in the end-fire direction. An ultra-wideband antenna designed for airborne ground-penetrating radar (GPR) applications operates from 300 MHz to 2 GHz, with a gain ranging from 4.4 to 11.5 dBi, as demonstrated through subsurface imaging [9]. Some of the techniques also include parasitic patches with double trapezoidal or elliptical patches [10, 11] and employing slot edges or dielectric lenses to extend frequency ranges and enhance radiation characteristics [12, 13]. Designs also focus on compactness and substrate versatility while maintaining low cross-polarization and stable gain across the UWB spectrum [14, 15], and some incorporate dual-polarized, radar cross-section (RCS)-reduced configurations for radar and near-field measurements [16]. Additionally, patch antenna arrays have been optimized for direction of arrival (DoA) estimation and mutual coupling mitigation in X-band applications [17], while circularly polarized slot and patch antennas have been designed for 5G and GPS to improve axial ratio bandwidth, gain, and frequency coverage [18, 19].

This article presents a novel Vivaldi antenna that has been both designed and tested. The bandwidth and gain of the proposed Circular Slots and Trapezium Parasitic Patch Vivaldi Antenna (CSTPP-VA) show significant performance improvement compared to the Coplanar Vivaldi Antenna (Co-VA) and the Circular Outer Edges Vivaldi Antenna (COE-VA) of similar dimensions. To enhance bandwidth, circular slots with an optimal radius were incorporated into the Co-VA, resulting in a modified design referred to as Circular Slots Vivaldi Antenna (COE-VA). The CSTPP-VA further integrates a trapezium-shaped parasitic patch to improve gain and impedance matching. This particular parasitic patch shape is designed to radiate the maximum portion of the beam in the end-fire direction through coupling with the radiating patch. The antenna supports UWB opera-

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doi:10.2528/PIERC25121002 Published by THE ELECTROMAGNETIC ACADEMY

tion with high gain while maintaining a compact size. Its applications include various UWB communication systems, such as short-range communication, ground-penetrating radar, and other related fields.

2. ANTENNA DESIGN

The conventional structure used for designing the coplanar Vivaldi antenna is constructed using a tapered slot in the patch geometry. The general formula for designing flares of a Vivaldi antenna is as follows [2].

$$y = l_1 e^{ax} + l_2 \tag{1}$$

$$l_1 = \frac{y_2 - y_1}{e^{ax_2} - e^{ax_1}} \tag{2}$$

$$l_2 = \frac{y_1 e^{ax_2} - y_2 e^{ax_1}}{e^{ax_2} - e^{ax_1}} \tag{3}$$

The parameters l_1 and l_2 in (2) and (3) correspond to the gradient coefficients and can be determined by the starting and ending points of the exponential curve. These points include (x_1, y_1) and (x_2, y_2). The coplanar Vivaldi antenna is designed in accordance with the proposed design framework, with all geometrical parameters subsequently defined. This conventional design can be modified using a parasitic patch to enhance the antenna's gain. To ensure that the antenna's bandwidth remains unchanged, slots were incorporated into the design. The dielectric material was selected based on its impact on performance and the level of losses it introduced.

The antenna consists of a radiating element with a coplanar feeding structure, and it is fabricated on an FR4 epoxy substrate with a relative permittivity of 4.4, a loss tangent of 0.02, and a thickness of 0.8 mm. The radiating elements are made of copper, and the port is matched to a 50 Ω impedance. The design is simulated using Ansys HFSS. The design parameters include the parameter $s = 0.25$ mm and a flare rate of 80. The overall taper length is $L_1 = 50$ mm, with a 2.5 mm distance between the edge and the circular slot. The copper sheet thickness is 0.05 mm. The coplanar feed has dimensions of 8.38 mm (B_1) ×9.6 mm (L_2) and a width of 1.8 mm (B_2). The circular slots have radius $r_1 = 4$ mm, $r_2 = 3$ mm, and $r_3 = 2.83$ mm. The total dimensions of the design are 60.5 mm×50 mm×0.8 mm. The trapezium side lengths are $P_1 = P_3 = 4.47$ mm, $P_2 = 8$ mm, and $P_4 = 4$ mm. The designed geometry is shown in Fig. 1.

3. PARAMETRIC OPTIMIZATIONS

In Fig. 2, a Vivaldi antenna design involves careful optimization of parameters to ensure a wide bandwidth and stable performance. Key factors include the slot widths 's', which significantly impact bandwidth, and the tapered length and rate, which must align with 's' to maintain performance. Elements like the tapered slot radius and 'nudge' influence power distribution and surface current density. The circular slot radius 'r_3' and the number of edge slots on the radiating patch help stabilize the operational band. A compact size is needed to

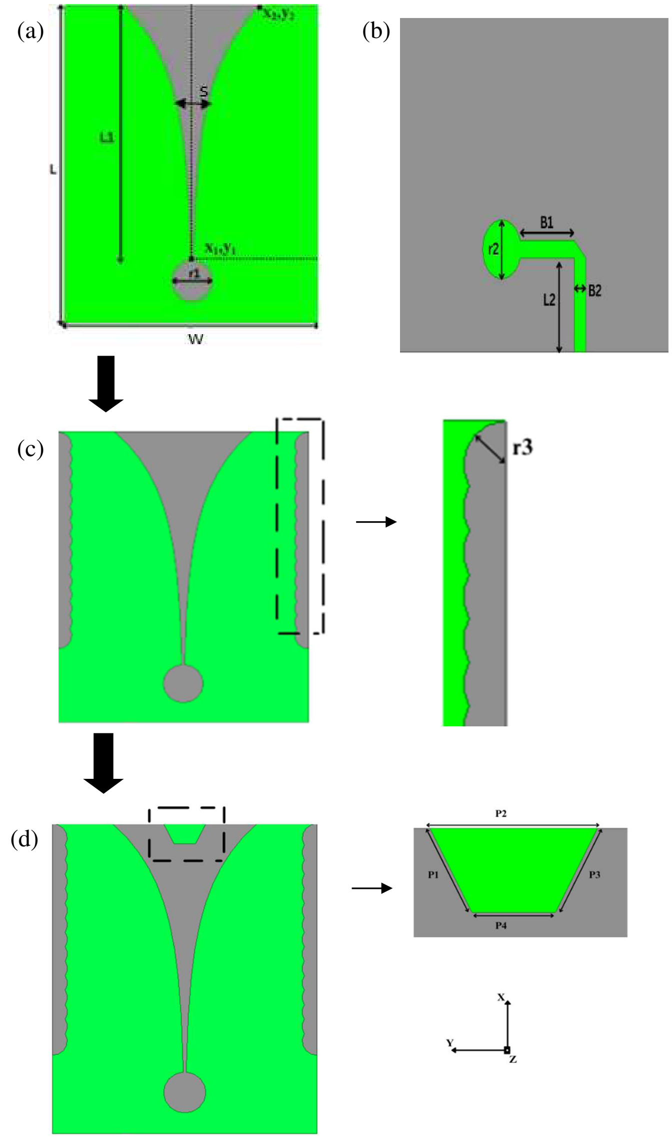

FIGURE 1. The proposed geometry of (a) Top view of Co-VA, (b) Bottom view of Co-VA, COE-VA & CSTPP-VA, (c) Top view of COE-VA, (d) Top view of CSTPP-VA.

support necessary applications requiring miniaturization. Similarly, Fig. 2 considers another parameter, i.e., the exponential rate of the length of the flare of the Vivaldi antenna patch. This parameter decides the curvature of the flares in the designed Vivaldi antenna, which plays an important role in maintaining proper layout and clean design. Variation shows much difference in obtained bandwidth, at lower rates, such as 50, and we can see the S_{11} increasing above −10 dB. Therefore, it has been increased slightly to check and attain great performance at 80, which keeps the whole plot below −10 dB, ensuring good bandwidth.

To understand the differences between various models at different stages of Vivaldi antenna design, simulations were conducted on several antenna parameters, and observations were recorded to track improvements at each stage. Fig. 3 illustrates how the bandwidth is influenced by variations in slot width. Lower slot width values exhibit better bandwidth performance

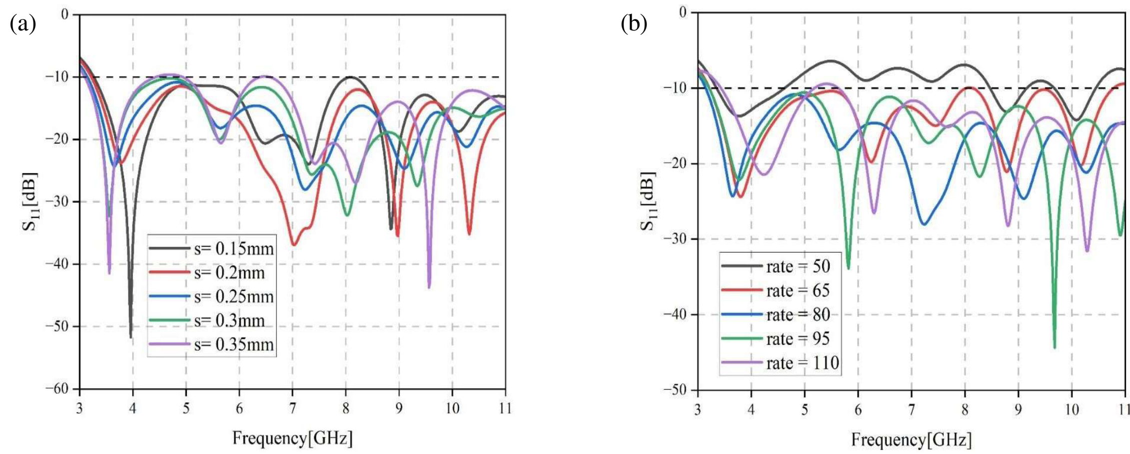

FIGURE 2. Parametric studies on the S_{11} by varying (a) parameter 's' and (b) flare rate.

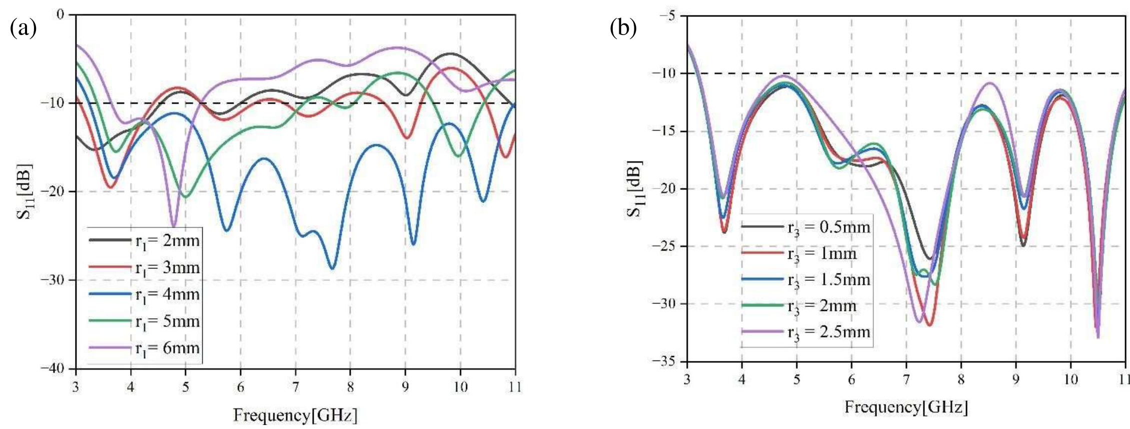

FIGURE 3. Parametric studies on the S_{11} by (a) r_1, and (b) r_3.

than higher values. The parameter $s = 0.15$ mm, and a higher reflection coefficient is observed at 4 GHz; however, the curve declines at 8 GHz, which is undesirable. Therefore, a slightly higher value of $s = 0.25$ mm provides better overall performance and is selected as the optimal parameter for the Vivaldi antenna. In essence, slot width has a critical role in maintaining optimal antenna performance and must be carefully analyzed to determine the best value.

In Figs. 3(a) and 3(b), the trends of S_{11} are observed when the radius of the tapered circular slots is varied.

The radius of the tapered slot on the top of the antenna r_1 is varied from 2 mm to 6 mm, while the radius of circular slots at the edges of the antenna r_3 is varied from 0.5 mm to 2.5 mm. It is evident from this plot that deviations are minimal in the case of variation in r_3 and maximum when considering r_1, thereby increasing the importance of tuning the parameters to maintain a proper reflection coefficient.

In Fig. 4, the simulated reflection coefficient of Co-VA, COE-VA, and CSTPP-VA is shown. The performance achieved a frequency range for UWB applications. The CSTPP-VA demonstrates a significant improvement in gain within the 3.2–11 GHz frequency range, as observed in Fig. 5, a spectrum widely utilized for various UWB antenna applications. The enhanced gain validates the effectiveness of the design for the targeted operating frequencies while also showcasing its strong penetration capability. The Co-VA and CSTPP-VA exhibit comparable gain performance, confirming that the addition of circular slots primarily impacts the bandwidth with minimal to no effect on gain. To further optimize performance, a parasitic patch is strategically positioned to enhance the antenna's gain while minimizing its impact on bandwidth.

In Fig. 6, the observation of the surface current distribution reveals a primary concentration near the tapered exponential slot line. These surface currents indicate the direction of radiation and also contribute to undesired radiation outside the main lobe. The above observations are interpreted based on the principle that the surface current distribution governs the radiation characteristics of an antenna, as derived from Maxwell's equations and the equivalence principle. Consequently, slots can be strategically introduced to suppress side-lobe radiation. By appropriately adjusting the slot lengths, a greater portion of the surface current can be captured, thereby improving the overall antenna performance.

4. EXPERIMENTAL RESULTS

The fabricated design satisfies all required specifications, and the measured parameters have been thoroughly evaluated and

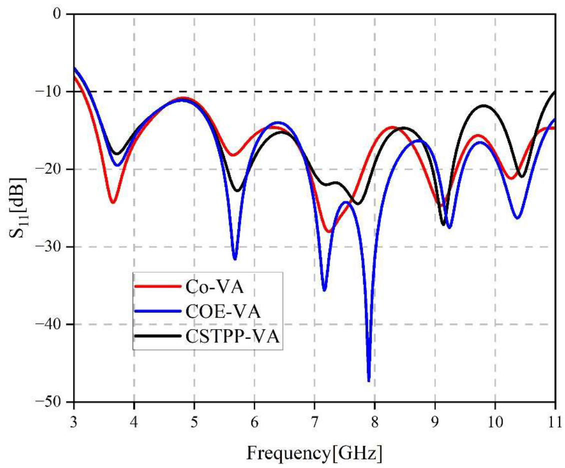

FIGURE 4. Simulation of the reflection coefficient for Co-VA, COE-VA, and CSTPP-VA.

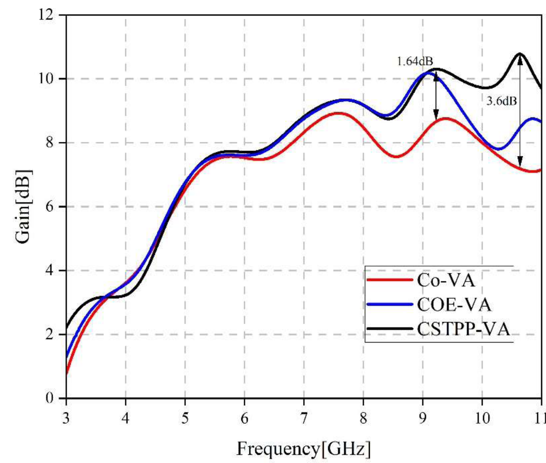

FIGURE 5. Simulated gain performance of Co-VA, COE-VA, and CSTPP-VA.

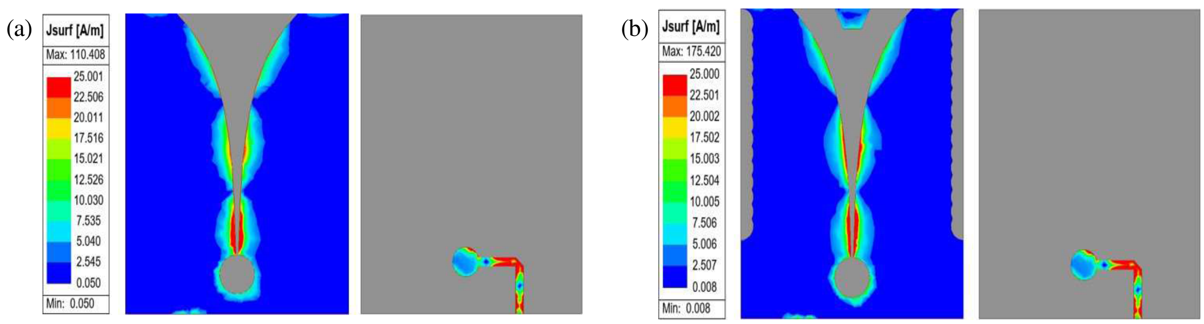

FIGURE 6. Surface current density of (a) Co-VA, (b) CSTPP-VA at frequency 7 GHz.

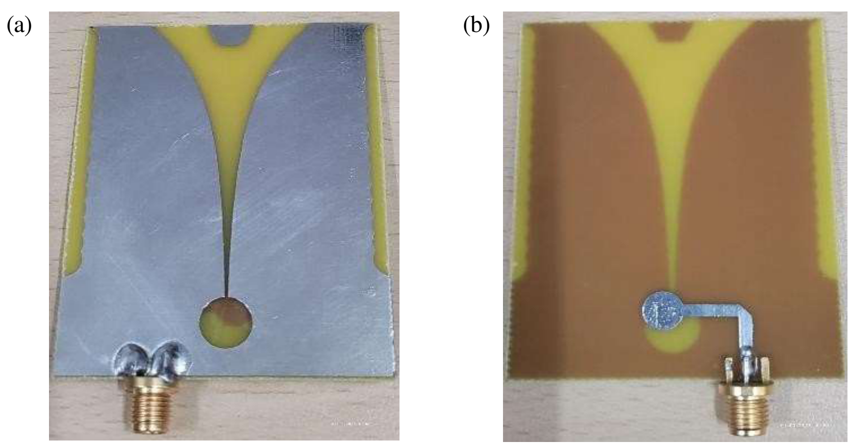

FIGURE 7. (a) Top view and (b) bottom view of the fabricated CSTPP-VA.

compared with the simulated results, with any discrepancies carefully noted. This evaluation is essential, as the fabrication outcomes confirm the accuracy of the overall design, emphasizing the need to account for all loss mechanisms during the simulation stage itself. Fig. 7(a) and Fig. 7(b) illustrate the top and bottom views of the fabricated antenna. Fig. 8 shows the measured S_{11} plot alongside the simulated response. While the measured curve exhibits slight distortion due to fabrication tolerances, it still satisfies the required bandwidth, and its resonant peaks appear as shifted versions of the simulated results. The gain of the fabricated antenna was also measured, yielding a peak value of 9.1 dB when the antenna was aligned in the H-plane. The Frills transmission formula is used to calculate the gain of the proposed antenna. Fig. 9 presents a comparison of the simulated and measured gain characteristics.

The radiation patterns were measured at 4.4 GHz and 8.3 GHz for both co-polarized and cross-polarized configu-

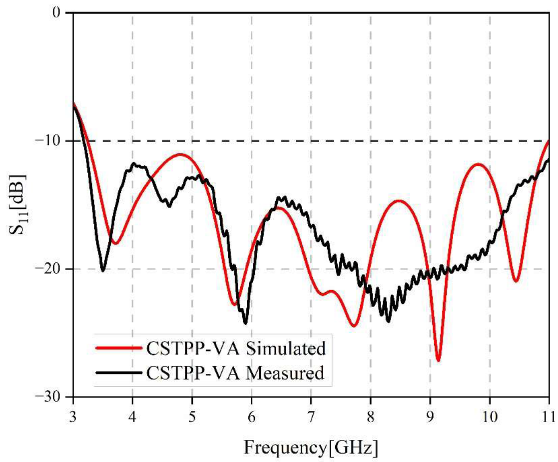

FIGURE 8. S_{11} comparison plot between simulated and measured CSTPP-VAs.

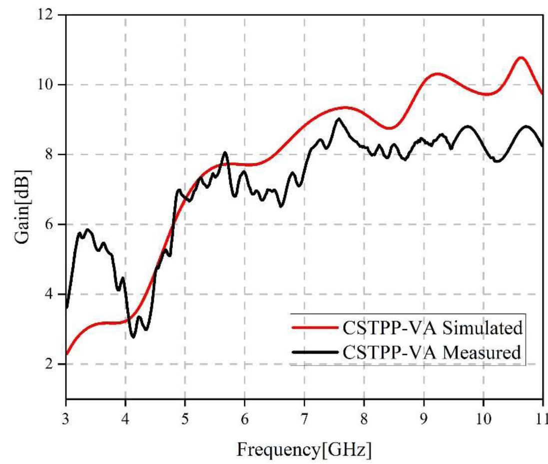

FIGURE 9. Gain comparison between simulated and measured CSTPP-VAs.

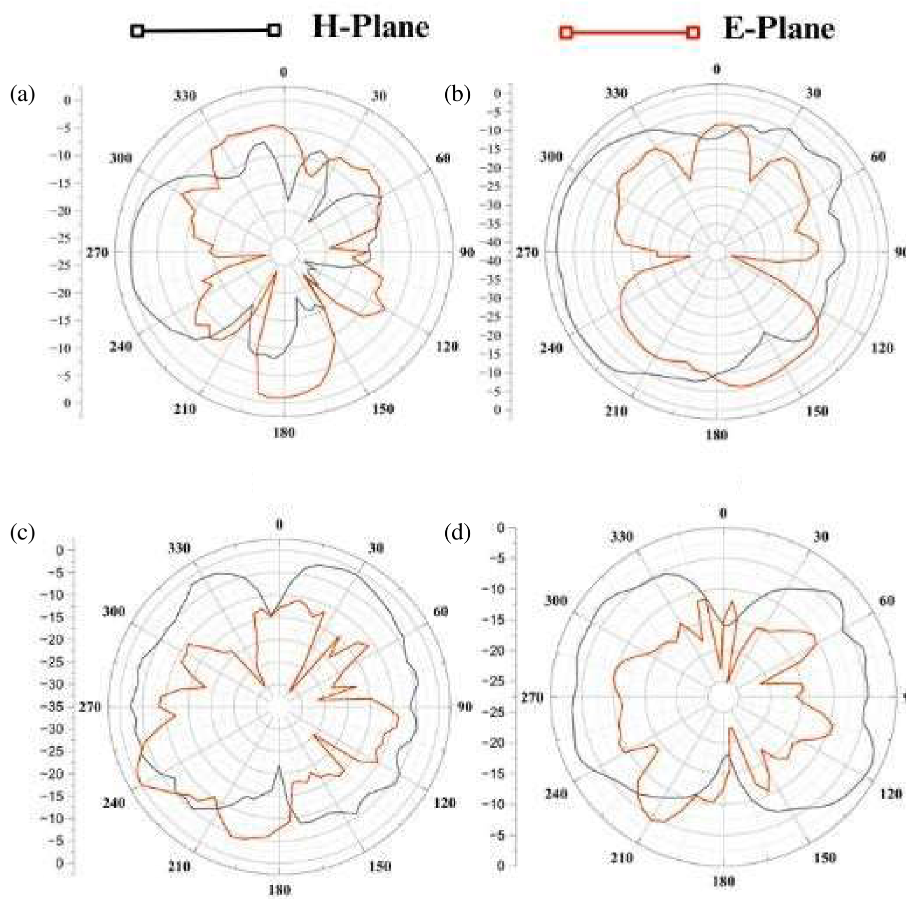

FIGURE 10. Radiation pattern of fabricated CSTPP-VA. At frequency (a) 4.4 GHz, (b) 6 GHz, (c) 8.3 GHz, and (d) 10 GHz.

rations, and the corresponding E-plane and H-plane plots are presented in Fig. 10. Cross-polarization refers to the case where the transmitting and receiving antennas are oriented in perpendicular planes, leading to significant signal interference, whereas co-polarization occurs when both antennas are aligned in the same plane, resulting in minimal interference. Fig. 11 shows that the antenna was tested in an anechoic chamber to assess its performance in a real-time environment. A standard ridge antenna (0.8–18 GHz) served as the transmitting antenna, with a measurement distance of 3 m. The parameters S_{11} were measured using an MS46122B Vector Network Analyzer (VNA). The antenna gain was determined using the Friis transmission equation along with the S_{21} readings obtained from the VNA. Minor deviations in slot radius mainly affect the impedance matching at higher frequencies, while slight misalignment of the parasitic patch results in small variations

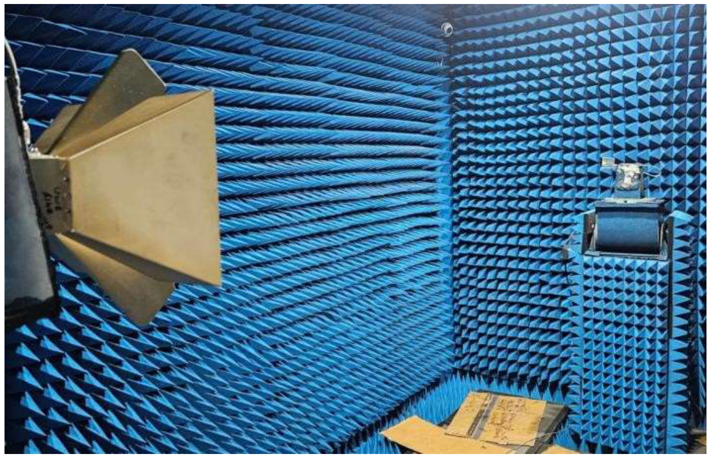

FIGURE 11. Anechoic chamber setup.

TABLE 1. Comparison between the proposed antenna and the existing antenna.

Ref	Size (mm^3)	Maximum-Gain (dB)	Bandwidth
[3]	$186\times77\times0.55$	16	2.5 GHz–57 GHz
[5]	$244\times195\times1.57$	9.82	450 MHz–10 GHz
[6]	$71.5\times83.4\times1$	24.1	3.8 GHz–>60 GHz
[9]	$450\times600\times1.5$	11.5	300 MHz–2 GHz
[10]	$124\times66\times1.575$	>9	6 GHz–26.5 GHz
[11]	$140\times66\times1.5$	>10	2 GHz–32 GHz
[15]	$94.82\times75\times1.74$	6.3	2.75 GHz–7.11 GHz
Our Work	$60.5\times50\times0.8$	9.1	3 GHz–>11 GHz

in the realized gain. As evident from Table 1, the proposed design achieves improved gain performance compared to the existing works.

5. CONCLUSION

The article explicitly defines the design and intricate analysis of Co-planar Vivaldi Antenna Circular slots and a Trapezium parasitic patch (CSTPP-VA) for ultra-wideband (UWB) applications. The use of circular slots increases bandwidth, while the trapezium parasitic patch adds directivity and gain. Performance measurements confirm that the CSTPP-VA achieves a peak gain of 10.77 dB, surpassing the conventional Coplanar Vivaldi Antenna (Co-VA), which has a maximum gain of 8.92 dB. The enhanced radiation efficiency and high-directivity of the CSTPP-VA make it a strong contender for various real-world applications, such as short-range communication, vehicle-to-vehicle (V2V) communication, and radar systems. The improved performance features indicate its potential for inclusion in next-generation wireless networks that demand effective ultra-wideband antennas. Further research on these antenna structures could explore optimization techniques, material development, and experimental analysis to improve the performance of the antenna in diverse domains, making it practical for communication systems.

ACKNOWLEDGEMENT

We sincerely thank Ms. Sudha R., Lab Instructor of the Antenna and Microwave Laboratory at Amrita School of Engineering, Coimbatore, for her valuable guidance and support in antenna measurements.

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