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A Miniaturized Double Sided Vivaldi Antenna with Enhanced Radiation Traits for EW Applications

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ABSTRACT: This paper presents a compact double sided Ultra-Wideband (UWB) Vivaldi antenna with a corrugated structure. The proposed antenna is designed to operate from 5 GHz to 20 GHz frequency band. A comprehensive analysis of the antenna is carried out for its design, optimization, and performance especially for enhanced bandwidth and improved radiation characteristics. The antenna structure consists of a Vivaldi section which is printed on top and bottom layers of a multi-layer printed circuit board (PCB) and fed with microstrip to strip lines transition. The antenna is fabricated, and its return loss and radiation characteristics are measured. The measured peak gain is 10.25 dBi at 17 GHz, and return loss is better than −10 dB over the band 5 GHz to 20 GHz. Symmetrical radiation properties are observed over the band with excellent radiation characteristics especially in lower frequency bands as a result of corrugated structure. Also, the far-field radiation pattern is symmetrical and directive throughout the operating band. The proposed design finds a suitable application in the field of an electronic warfare, precision ranging, and microwave imaging.

1. INTRODUCTION

Vivaldi antenna, also known as Vivaldi notch antenna emerged as a prominent choice because of its unique features such as Ultra-Wideband (UWB) operation, high gain, and radiation pattern with good cross polarization. Vivaldi antennas are more preferred over microstrip patch antennas because of ultra-wideband capabilities and broad angle scanning capabilities that make them suitable for industry and military applications such as radars, microwave imaging, satellite communication, and electronic warfare applications [1].

Vivaldi antenna is commonly realized with printed circuit technology on single layer as well as multilayer process. A resistance loaded dual layer printed Vivaldi antenna with a wide bandwidth from 2 GHz to 16.3 GHz is presented [2].

The resistance loading in the radiating section improves the impedance matching at lower frequency range. Another advantage of resistive loading in the antenna design is to make it compact. However, above approach significantly compromises the gain and efficiency of the antenna.

In [3], a printed Vivaldi antenna has UWB capabilities from 3.1 GHz to 20 GHz. A linear corrugated structure is used for impedance matching at low frequencies and size reduction. However, above approach does not significantly improve the gain profile at lower band of operating frequency range. Moreover, compact Vivaldi antennas experience issues with splitting the radiation patterns in the higher frequency range of the bandwidth.

Gain enhancement techniques for Vivaldi antenna is presented using printed apertures along the direction of radiation [4] and metamaterials for breast imaging applications [5]. In [4, 5], some sort of apertures is used in the antenna, but it restricts the bandwidth.

Feeding technique for Vivaldi antenna is one of the challenging parts of the design. The key parameters to design these kinds of transitions are UWB characteristics with low loss and compatible integration with improved mechanical and electrical functionalities [6]. As per state of art, significant work has been established to improve the performance using quarter wave balun feeding [7], microstrip to double sided parallel strip line [8, 10], 3D printed Vivaldi antenna fed with transmitting-receiving modules [9], substrate integrated waveguide (SIW) fed Vivaldi antennas [11]. Microstrip to strip line transition is optimum for mechanical and electrical compatibility with excellent UWB transition features.

In this paper, a compact double sided Vivaldi antenna with corrugated structure fed with microstrip to strip line transition is proposed for the frequency from 5 GHz to 20 GHz. The main objective of this work is to design a compact, high gain UWB antenna with stable radiation patterns and to overcome a problem of main beam splitting at higher frequencies.

The realized compact double sided Vivaldi antenna (DSVA) is characterized through extensive experimentation, and its performance is compared to conventional antenna design. Improved radiation characteristics including gain enhancement and stable radiation pattern with a minimum peak gain at boresight of 4 dBi are observed from 5 GHz to 20 GHz in the measured results. Furthermore, the antenna exhibits excellent gain profile, low cross-polarization levels, and improved radiation properties, making it suitable for a wide range of applications.

It can be noted that a strip radial stub having radius r_1 with arc length of 105 deg is chosen, which comprises all combinations of quarter wavelengths in operating frequency range

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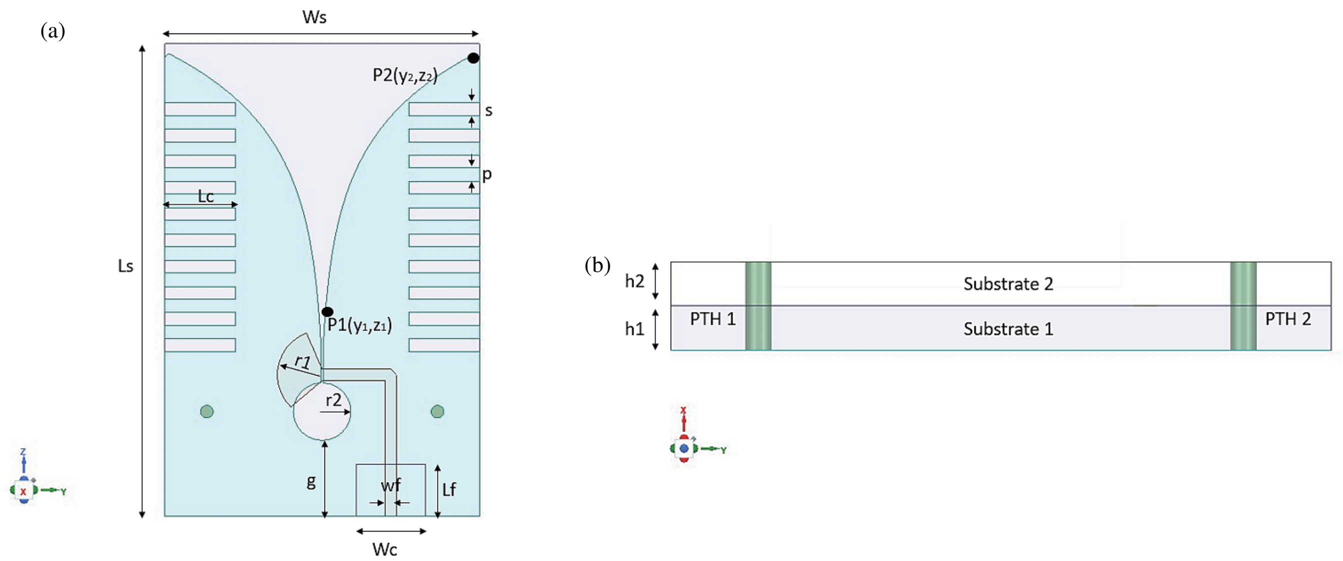

FIGURE 1. Proposed antenna (a) top view, and (b) cross-sectional view.

for good impedance matching. The design process involves several stages, including substrate selection, radiating element configuration, transition design, and optimization. The impact of various geometrical parameters on antenna performance is thoroughly investigated using full-wave electromagnetic simulations, and solver performs finite element method (FEM) using ANSYS.

2. DESIGN PROCEDURE

2.1. Vivaldi Antenna Design

The design starts with elementary Vivaldi antenna design. Afterward, single and two sided corrugated structures are integrated with the antenna. The double sided Vivaldi antenna is chosen because of compactness in nature, high gain, and good end fire radiation characteristics [1]. Noteworthy progress can be observed in the evaluation from the basic Vivaldi design to the compact double sided Vivaldi antenna as shown in Fig. 1.

The minimum width W_{ant} of the slot antenna is more than half of the free space wavelength at particular frequency (f) and can be presented by

$$W_{ant} \geq \frac{\lambda_0}{2} \quad \text{where} \quad \lambda_0 = \frac{c}{f}. \tag{1}$$

where f is the frequency, c the velocity of light, and λ_0 the free-space wavelength.

The maximum and minimum widths of the slots correspond to f_{min} and f_{max} frequencies respectively in the exponential profile respectively [1].

Here, z-axis is considered the direction of radiation, and the exponential profile of the antenna in 2 is defined by

$$z = A_1 e^{R.y} + A_2. \tag{2}$$

where

$$A_1 = \frac{z_2 - z_1}{e^{R.z_2} - e^{R.z_1}} \quad \text{and} \quad A_2 = \frac{z_2 e^{R.y_2} - z_1 e^{R.y_1}}{e^{R.y_2} - e^{R.y_1}}$$

A_1 and A_2 are constants for desired exponential profile, and R is the responsible factor in tapered profile for impedance matching over the operating band and radiation efficiency. Extreme points of radiating section of proposed antenna are assumed as $p_1(y_1, z_1)$ and $p_2(y_2, z_2)$ shown in Fig. 1. The design parameters of corrugated structures $L_c = 0.12\lambda_0$, $s = 0.02\lambda_0$, and $p = 0.04\lambda_0$, which are calculated at 5 GHz, are incorporated in the Vivaldi structures to enhance radiation characteristics at lower frequency band.

2.2. Feeding Mechanism and Transition

Microstrip to strip line transition is chosen here, which is shown in Fig. 2. Microstrip line is exposed through a rectangular cutout, facilitating the assembly of connector to this microstrip line. Following the microstrip section, the strip line segment starts and connects to the proposed antenna. The transition width is optimized to attain the desire bandwidth. The antenna adopts a multilayer-layer Vivaldi design, sandwiching the feeding strip in the middle, to mitigate excessive interference.

Initially, 50 Ω coaxial connector is used to excite the antenna through microstrip line. The widths of the microstrip line and strip line are calculated as 1.5 mm and 0.75 mm, respectively, using the help of commercial EM simulator. However, upon realizing transition design ripples were observed in the return loss, and then the width optimization for the feed line is performed to achieve optimal performance in the operating frequency band.

The cavity radius r_2 is also a critical parameter as far as impedance matching is concern. Spacing along the direction of radiation (z-axis) between cavity and strip stub should be close enough for tight coupling [7, 8].

If strip open circuited impedance Z_{ocm} and cavity based short circuited impedance Z_{scc} are defined as the function of r_1 and r_2, respectively [6–11], then the input impedance of the

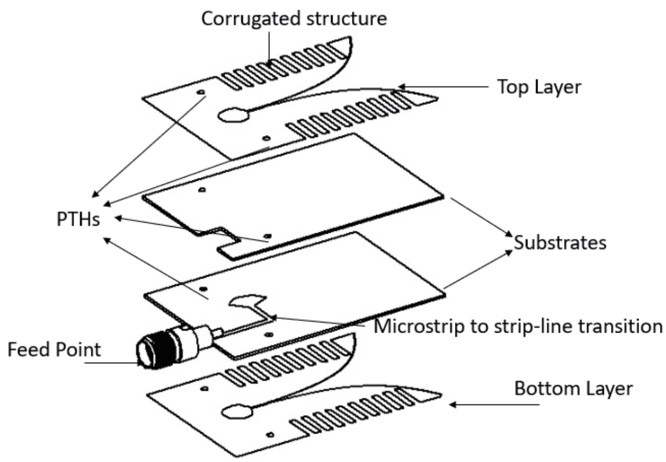

FIGURE 2. Geometry of the proposed antenna.

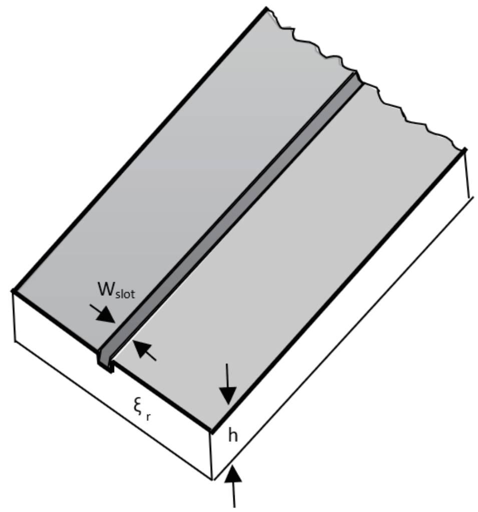

FIGURE 3. Microstrip slot line configuration.

slot line Z_{slot} is defined by

$$Z_{slot} = \sqrt{Z_{ocm} Z_{scc}}. \tag{3}$$

Now, the width of the slot at the starting point of the radiating section of proposed antenna is a function of Z_{slot} formulated in Equation (4)

$$W_{slot} = f(Z_{slot}). \tag{4}$$

A substrate having a permittivity ξ_r and thickness h is considered and shown in Fig. 3. The input impedance of microstrip slot line and width of the slot line W_{slot} can be formulated for low permittivity substrate[13], and W_{slot} can be derived by

$$W_{Slot} = \frac{h}{2.12}\sqrt{K\left(Z_{slot} - 50(approx)\right)} \tag{5}$$

where h is the substrate thickness. The characteristic impedance typically ranges from $70\,\Omega$ to $90\,\Omega$ for optimal matching with strip lines, and K is the slope factor which is $0.02\,\text{mm}/\Omega$ as per W_{slot} and Z_{slot} curve fitting. Equation (5) is obtained using curve fitting of the parameters, i.e., dielectric constant ranging from 2 to 5 and thickness of the substrate from 0.508 mm to 1.568 mm. Formulation is used for the calculation of microstrip slot line width [12, 13] for impedance $40\,\Omega$ to $100\,\Omega$. W_{Slot} is initially calculated as 0.35 mm, as per (5), and optimized value is determined to be 0.2 mm.

2.3. Configuration of the Proposed Antenna

Configuration of the proposed antenna is shown in Fig. 2. The structure of the antenna consists of three sections: feeding section, transition section, and radiating section. The antenna is fed using a $50\,\Omega$, 2.92 mm K-connector placed on a metal plate as reflector ground. Here, microstrip to strip-line transition design is a vital part of the process. It is chosen for electrical and mechanical feasibilities and to avoid many critical challenges. Radiating section consists of exponential TSA profile on top and bottom layers as per mathematical expression (2). The double-sided tapered structures are shorted through plated through holes (PTHs). The main purpose of PTHs is to make a short between the top and bottom layers. Locations and number of PTHs do not affect the performance. Short circuited radial cavity (r_2) is unified at one end. Impedance matching is performed using an open ended strip radial stub (r_1) with 105° of arc length for the proposed structure. A corrugated structure is introduced and optimized in the proposed antenna for the enhancement of gain and bandwidth in the lower frequency band specially. The corrugated structure is composed of N rectangular slots which have length L_c and width s, and the pitch between them is p. Ground offset (g) is sufficiently large to avoid abrupt changes in current distribution and get rid of reflections.

In order to accomplish impedance matching and maximum power transfer to the radiating section, slot line and exponential profile with specific tapered rate (R) plays a critical role. The value of R more than 0.1 lies under the category of linear tapered profile, which does not support UWB performance. For exponential tapered profile, R is chosen as 0.03 in the range of 0.01 to 0.09 [7]. Implicitly, the proposed structure provides good UWB characteristics with enhanced radiation properties.

3. PERFORMANCE ANALYSIS

The proposed antenna as shown in Fig. 1 is realized using a TLY-5 substrate with a total thickness 1.016 mm and having 35 µm copper fins with gold finish on both sides. The total length and width of the antenna are 45 mm and 30 mm, respectively. Width of the antenna is sufficiently wide to eliminate reflections. All dimensions and calculations are carried out for considering lower cut-off frequency at 5 GHz.

The design starts with a single sided Vivaldi antenna without corrugation (SSVA) shown in Fig. 4(a). In its compact configuration, SSVA exhibits an excellent gain profile, and yet it faces challenges in maintaining linearity in peak gain. Simultaneously, ripples above -10 dB are observed in return loss.

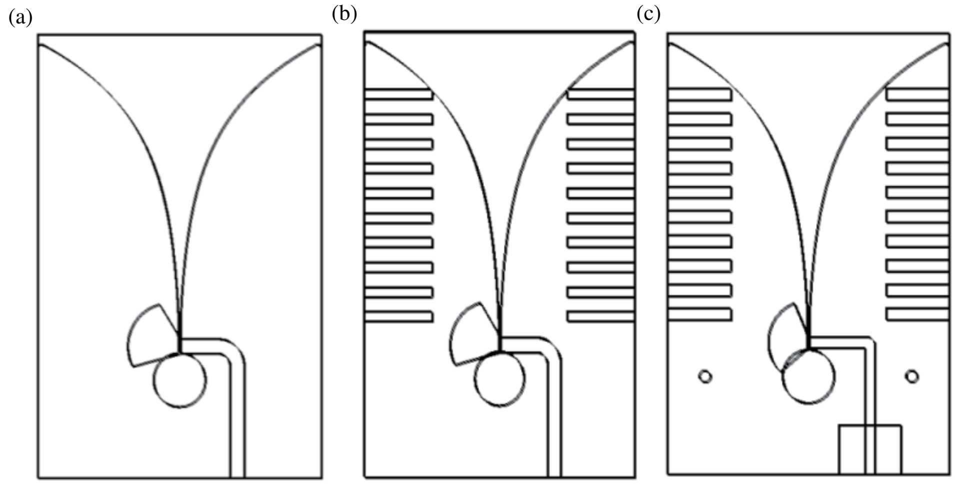

FIGURE 4. Antenna configurations. (a) SSVA, (b) corrugated-SSVA, and (c) corrugated-DSVA.

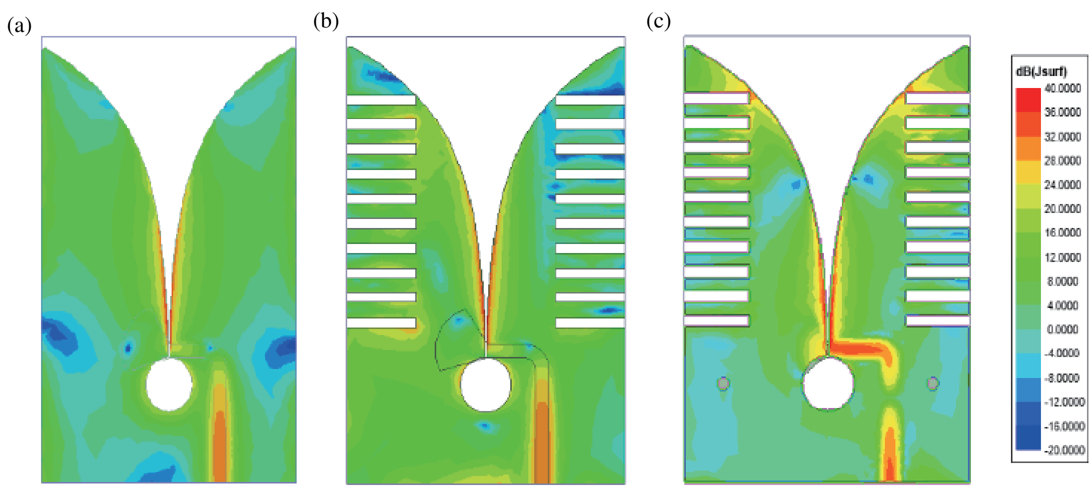

FIGURE 5. Current density at 5 GHz. (a) SSVA, (b) corrugated-SSVA, and (c) corrugated-DSVA.

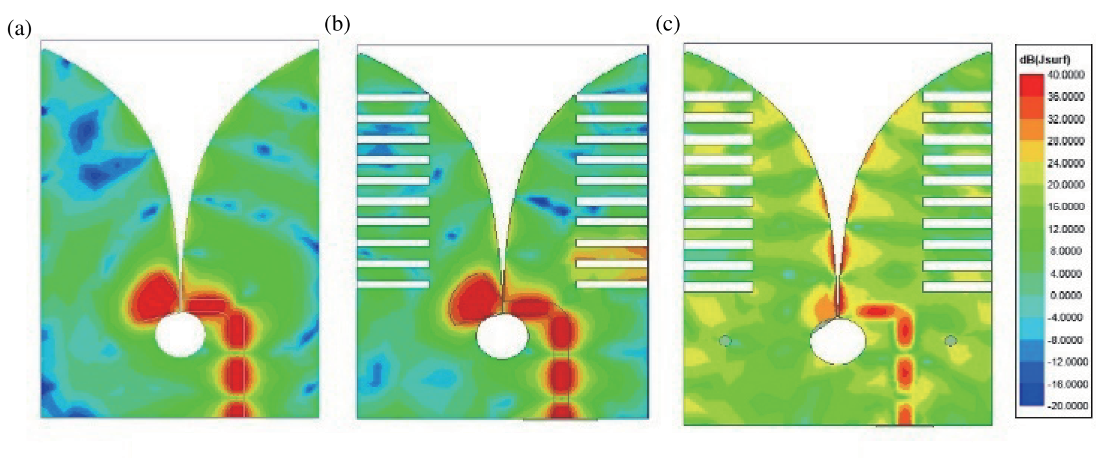

FIGURE 6. Current density at 20 GHz, (a) SSVA, (b) corrugated-SSVA, (c) corrugated-DSVA.

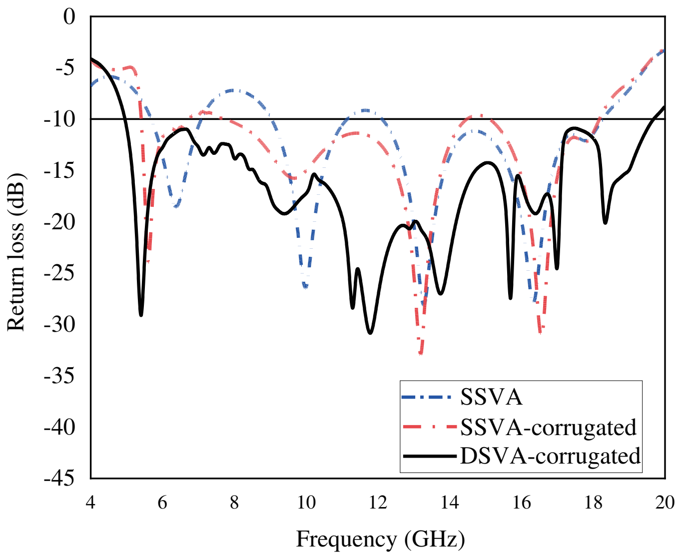

FIGURE 7. Comparison in simulated return losses of SSVA, corrugated-SSVA, and corrugated-DSVA.

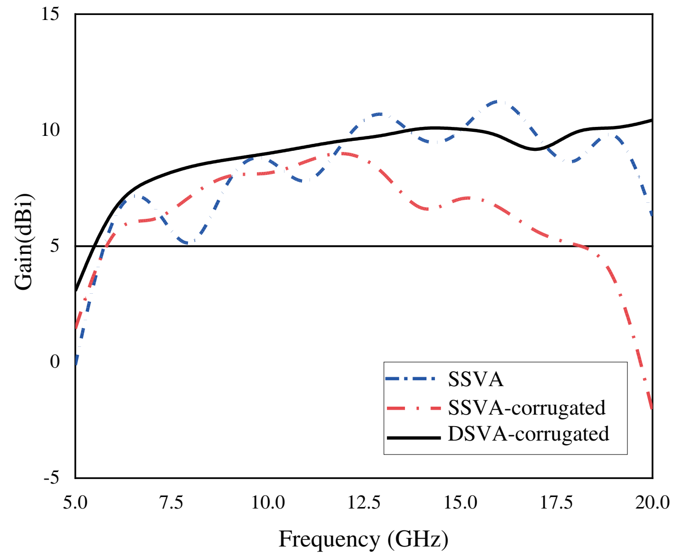

FIGURE 8. Comparison in simulated gains (dBi) of SSVA, corrugated-SSVA, and corrugated-DSVA.

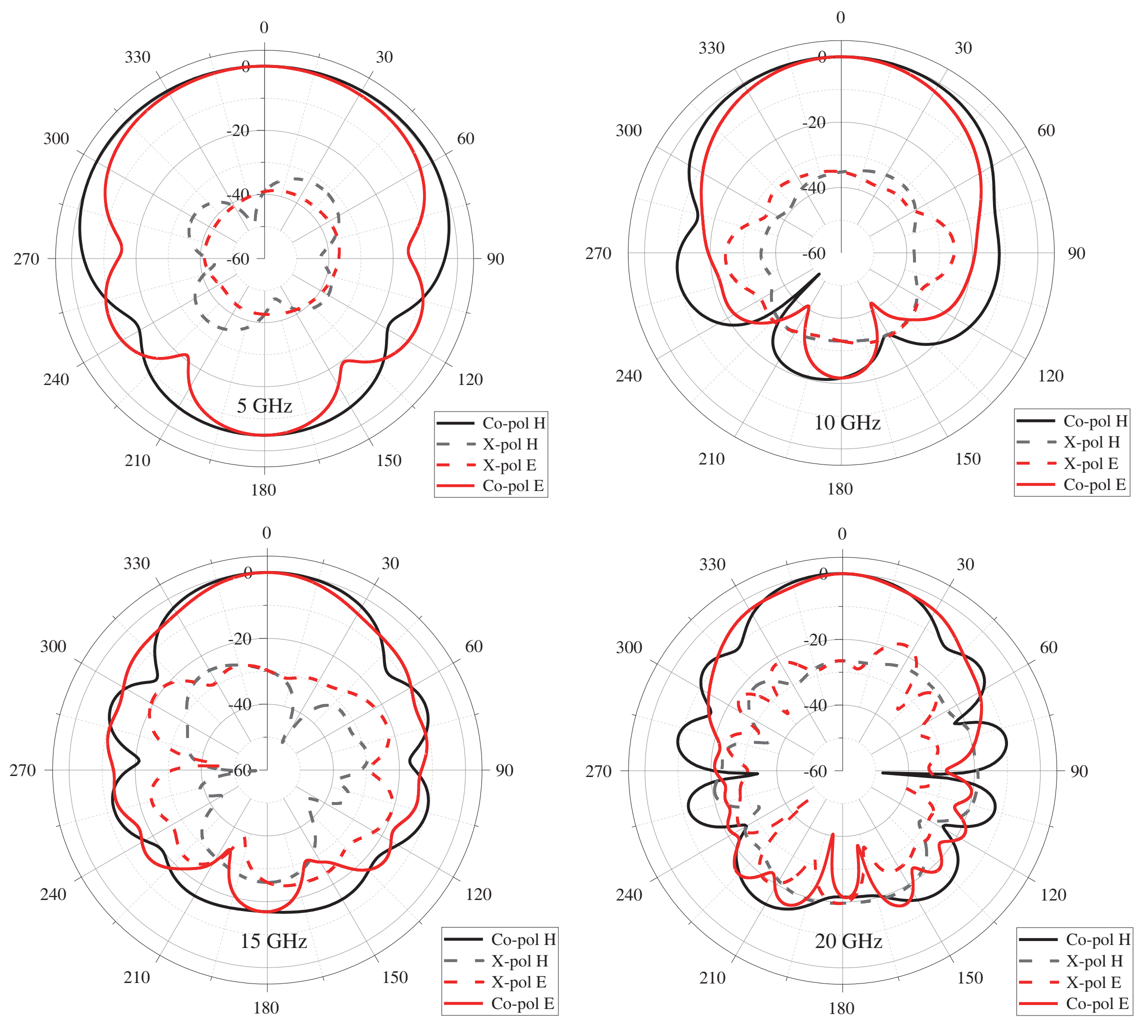

FIGURE 9. Simulated radiation pattern of proposed antenna in E and H plane.

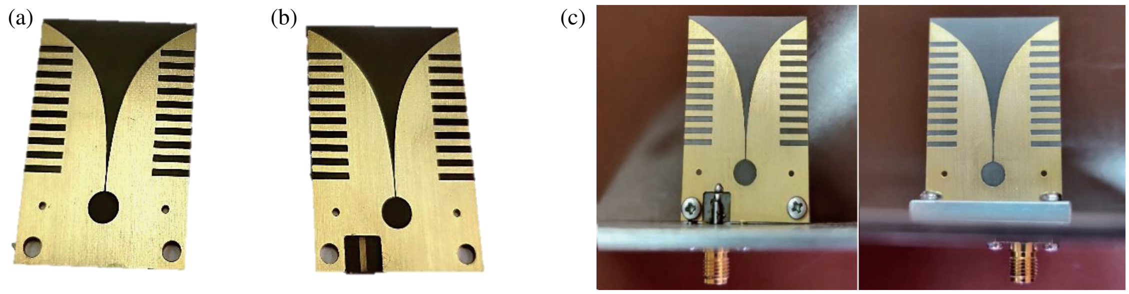

FIGURE 10. Photograph of fabricated PCB and assembled antenna, (a) top Layer, (b) bottom Layer, (c) assemble antenna.

TABLE 1. Design parameters and optimized value of proposed antenna.

Design Parameters	Description	Optimized Value (mm)
L_s	Length of the substrate	45
W_s	Width of the substrate	30
r_1	Radius of microstrip Radial stub	4.2
r_2	Cavity Radius	3
g	Ground offset	7.5
L_c	Length of corrugated unit	6.75
s	Width of corrugated unit	1.2
p	spacing between Corrugated units	1.3
w_f	Width of feed line	1
$W_c \times L_f$	Pattern Area for Feeding	6.6×6

To improve the return loss and radiation characteristics, corrugated structure is incorporated (corrugated-SSVA) which is shown in Fig. 4(b). It shows an excellent linear gain profile up to 15 GHz. It is observed that above 15 GHz, the gain decreases at boresight due to beam-splitting. It is observed that in tapered slot antennas ,gain reduction and beam splits at the bore side due to current distribution profile starts cancelling when size of the radiating arms exceeds λ. The proposed corrugated-DSVA structure shows a significant change in bandwidth as shown in Fig. 4(c) with excellent linear gain profile up to 20 GHz. This structure mitigates the issue of gain decrement at higher frequency bands by ensuring a consistent current distribution profile.

In Fig. 5, current density distribution at 5 GHz is depicted for antennas works with different structures illustrated in Fig. 4. The amplitude of the current distribution indicates enhancement in lower frequency region, attributed to the corrugated profile in the proposed antenna.

This significantly impacts gain enhancement and radiation efficiency for compact structures. The addition of a same Vivaldi structure on the other side of substrate compels the current distribution to align in the same phase, as illustrated in Fig. 6.

Furthermore, the proposed element, SSVA, and corrugated-SSVA configuration are presented in Fig. 4. For all three antennas, performances are simulated. The corresponding return loss is shown in Fig. 7.

Corrugated-DSVA exhibits a significantly response in impedance bandwidth from 5 GHz to 20 GHz, where return loss is better than -10 dB. Fig. 8 also displays a gain assessment among the mentioned structures. Gain of the proposed element demonstrates an admirable profile with such a compact multilayer design and exceptional radiation characteristics across 5 GHz to 20 GHz frequency band. The optimized values of design parameters for the proposed antenna are shown in Table 1.

4. SIMULATED AND MEASURED RESULTS

The Antenna is designed and simulated using commercially available EM simulator Ansys HFSS. Fig. 9 shows the simulated normalized 2-dimensional radiation pattern considering XZ (Ø = 0°) as E-plane and YZ (Ø = 90°) as H-plane. Co and cross pole radiation patterns are plotted for 5 GHz, 10 GHz, 15 GHz, and 20 GHz, respectively. The patterns show that the main beam is directed boresight with end fire characteristics in co- and cross-polarization levels, which is better than -25 dB throughout the operating frequencies. The proposed antenna structure has tapering profile with a corrugated structure on both sides of the substrate. As a result, it allows better impedance matching and reduced reflections leading to improved cross-polarization performance compared to other conventional Vivaldi antennae.

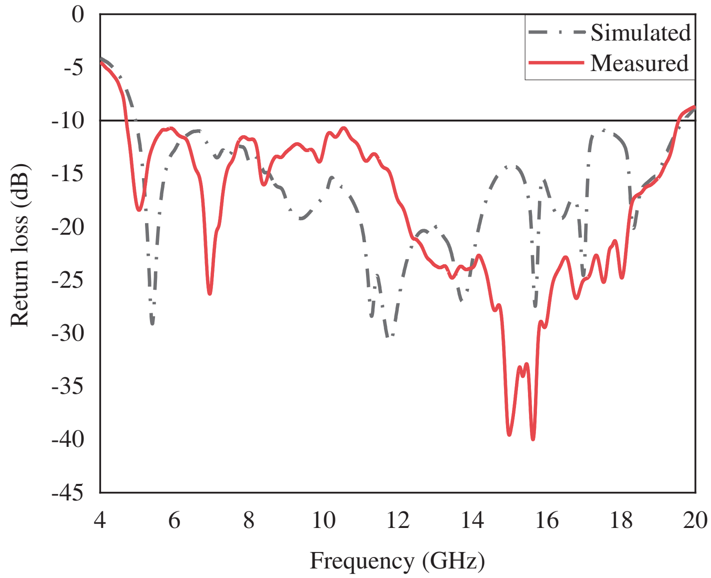

FIGURE 11. Simulated and measured return losses (dB) of the proposed antenna.

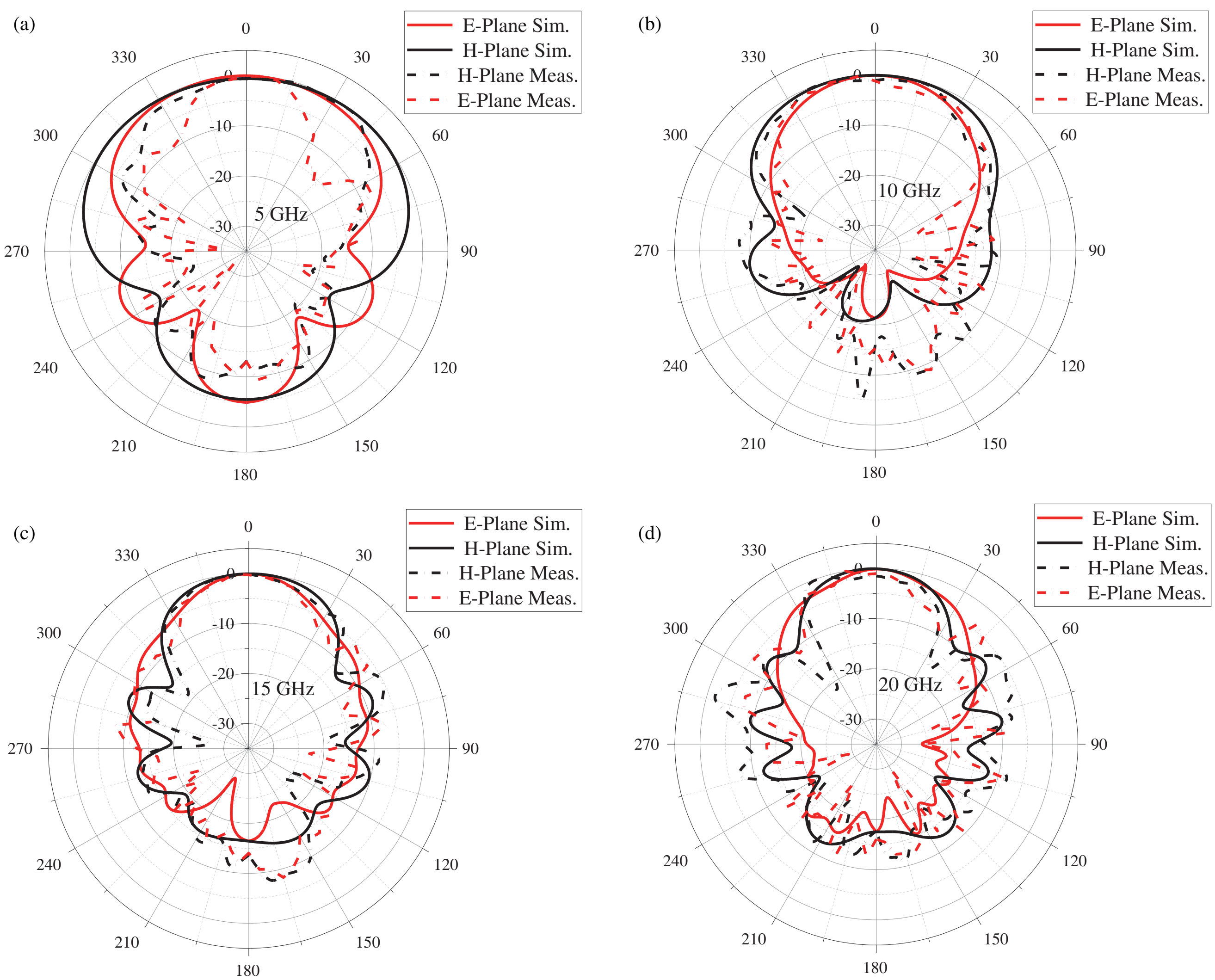

FIGURE 12. Simulated and measured radiation patterns of the proposed Antenna. (a) 5 GHz, (b) 10 GHz, (c) 15 GHz, and (d) 20 GHz.

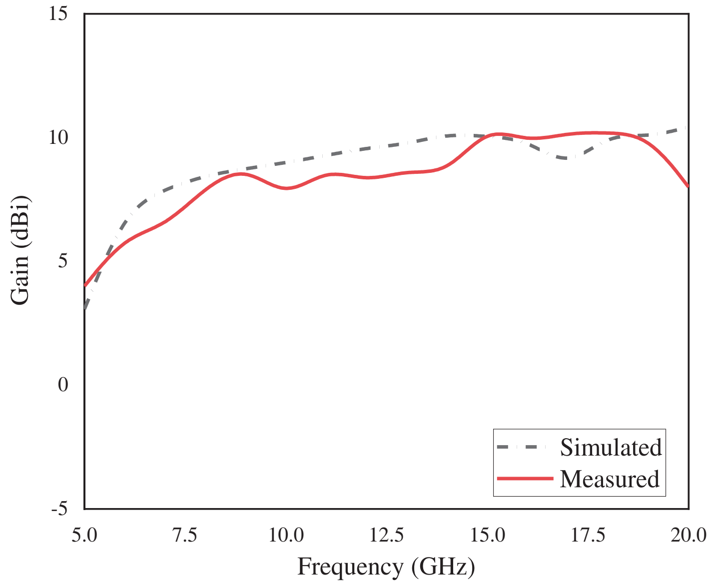

FIGURE 13. Simulated and measured gain profiles of the proposed antenna.

Figure 10 displays photographs of the four-layer fabricated PCB (top and bottom layer) realized using multilayer fabrication process and assembled antenna on metal base plate serving as a reflector ground. The measured and simulated return losses of the antenna are shown in Fig. 11.

The simulated and measured radiation patterns are presented in Fig. 12. The antenna offers half power (3 dB) beamwidths in the E-plane of 100°, 60°, 50°, and 55° and in the H-plane 90°, 80°, 40°, and 70° at 5 GHz, 10 GHz, 15 GHz, and 20 GHz, respectively.

In general, at low frequency, gain is reduced as surface currents travel outward from the center of aperture [15, 16]. The realized antenna is unified with a corrugated structure to prevent surface currents at low frequency from traveling outwards, resulting in a significant gain improvement the lower frequency band [3].

5. CONCLUSION

This paper investigates a compact, double sided multilayer compact Vivaldi antenna with a corrugated structure fed with microstrip to strip line transition. Comparative studies are conducted for multiple configurations including SSVA, corrugated-SSVA, and corrugated-DSVA (proposed). The Vivaldi antenna exhibits beam squint and ripples in the radiation pattern at higher frequencies. The proposed antenna demonstrates a substantial stable radiation pattern and gain across the entire band from 5 GHz to 20 GHz, suitable for beam forming and scanning in UWB applications. Furthermore, the realized antenna element can be scaled for an 8×8 array accumulated in a triangular lattice to avoid grating lobes in higher frequencies for electronic warfare (EW) domain providing an estimated peak gain profile at boresight from 19 dBi to 25 dBi in the operating frequency band.

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REFERENCES

[1] Saleh, S., W. Ismail, I. S. Z. Abidin, M. H. Jamaluddin, M. Bataineh, and A. Alzoubi, "Simple compact UWB Vivaldi antenna," in *Proceedings of the 11th International Conference on Robotics, Vision, Signal Processing and Power Applications*, Vol. 829, 13–19, 2022.

[2] Zhao, C., X. Li, M. Yang, and C. Sun, "Resistance-loaded miniaturized dual-layer vivaldi antenna for plasma reflection diagnosis," *Microwave and Optical Technology Letters*, Vol. 63, No. 1, 205–210, 2021.

[3] Naik, K. S., D. Madhusudan, and S. Aruna, "Slot tapered vivaldi antenna with corrugated edges," *Advanced Science and Technology Letters*, Vol. 147, 142–149, 2017.

[4] Guruswamy, S., R. Chinniah, and K. Thangavelu, "Design and implementation of compact ultra-wideband vivaldi antenna with directors for microwave-based imaging of breast cancer," *Analog Integrated Circuits and Signal Processing*, Vol. 108, 45–57, 2021.

[5] Islam, M. T., M. T. Islam, M. Samsuzzaman, H. Arshad, and H. Rmili, "Metamaterial loaded nine high gain Vivaldi antennas array for microwave breast imaging application," *IEEE Access*, Vol. 8, 227 678–227 689, 2020.

[6] Manteghi, M. and Y. Rahmat-Samii, "A novel UWB feeding mechanism for the TEM horn antenna, reflector IRA, and the Vivaldi antenna," *IEEE Antennas and Propagation Magazine*, Vol. 46, No. 5, 81–87, Oct. 2004.

[7] Dzagbletey, P. A., J.-Y. Shim, and J.-Y. Chung, "Quarter-wave balun fed Vivaldi antenna pair for V2X communication measurement," *IEEE Transactions on Antennas and Propagation*, Vol. 67, No. 3, 1957–1962, Mar. 2019.

[8] Zhou, Y., J. Huang, W. Wu, and N. Yuan, "A printed LPDA antenna fed by a microstrip line to double sided parallel strip line from backside," *International Journal of Antennas and Propagation*, Vol. 2017, Article ID 6259682, 2017.

[9] Gjokaj, V., J. Papapolymerou, J. D. Albrecht, B. Wright, and P. Chahal, "A compact receive module in 3-D printed Vivaldi antenna," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 10, No. 2, 343–346, Feb. 2020.

[10] Li, X., Y. Wang, H. Zhan, and Y. Zhang, "Design of an ultra-wideband transition from double-sided microstrip to parallel-strip line for balanced-type antenna," *Recent Advances in Electrical & Electronic Engineering (Formerly Recent Patents on Electrical & Electronic Engineering)*, Vol. 11, No. 1, 76–79, 2018.

[11] Puskely, J., T. Mikulasek, J. Lacik, Z. Raida, and H. Arthaber, "SIW-fed Vivaldi antenna with beam steering capabilities," *Microwave and Optical Technology Letters*, Vol. 59, No. 5, 1022–1027, 2017.

[12] Garg, R., I. Bahl, and M. Bozzi, *Microstrip Lines and Slotlines*, Artech House, 2013.

[13] Yusof, K. H., N. Seman, M. H. Jamaluddin, and D. N. A. Zaidel, "Characterization and formulation of microstrip-slot impedance with different thickness and relative permittivity," *Applied Mechanics and Materials*, Vol. 781, 53–56, 2015.

[14] Tahar, Z., X. Derobert, and M. Benslama, "An ultra-wideband modified Vivaldi antenna applied to through the ground and wall imaging," *Progress In Electromagnetics Research C*, Vol. 86, 111–122, 2018.

[15] Saeidi, T., I. Ismail, W. P. Wen, A. R. H. Alhawari, and A. Mohammadi, "Ultra-wideband antennas for wireless communication applications," *International Journal of Antennas and Propagation*, Vol. 2019, Article ID 7918765, 2019.

[16] Premchand, K., H. Paik, and S. K. Mishra, "Stripline fed slotted edge balanced antipodal Vivaldi antenna for advanced radar applications," *Progress In Electromagnetics Research Letters*, Vol. 103, 119–126, 2022.

[17] Sathishkannan, P., R. K. Singh, A. Jindal, S. Singh, and S. Varughese, "Compact 5-18 GHz Vivaldi-like antenna for airborne EW phased array applications," in *2023 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON)*, 1–5, 2023.