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Stripline Fed Slotted Edge Balanced Antipodal Vivaldi Antenna for Advanced Radar Applications

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Abstract—A compact exponentially tapered balanced antipodal Vivaldi antenna for modern radar systems is proposed in this paper. The proposed design implements slanted rectangular slots at the flare edges to improve impedance bandwidth typically at lower frequencies. The antenna is coupled to a $50\,\Omega$ microstrip line between the signal conductors of the middle layer and ground plane. A detailed parametric analysis has been carried out to determine the optimized dimensions and to achieve desired antenna performance. A prototype of the antenna ($56 \times 28 \times 1.6\,\mathrm{mm}^3$) was fabricated and measured to validate the simulation results. It is revealed that the antenna has a wide impedance bandwidth of 120% over 5–20 GHz and measured gain of the antenna increases from 2.6 dB to 8.0 dB in the whole operational frequency band. The small aperture width which is typically 28 mm is an attractive feature of the proposed design. Therefore, compact size, high gain, ultrawide bandwidth, and directional radiation characteristics of the proposed design may be suitable for advance radar systems.

1. INTRODUCTION

In recent days, broadband antennas have received significant demand in the field of electronic warfare for weapon control and missile guidance applications because of their attractive features including ultra-wideband (UWB), high gain, and directional patterns [1]. Further, the recent development in the modern radars has increased the demand for the design of broadband antennas. Still significant challenges exist to achieve large bandwidth, high gain, and compactness in these applications [2, 3]. However, multi-octave performance based UWB antennas have been the best choice for multi-mode radars and missile approaching warning receivers. Of several antennas employed in wideband arrays and multi-mode radar systems, multi-octave Vivaldi antennas and their variants are mostly preferred due to large impedance bandwidth, high gain, symmetrical beamwidth, and excellent broadband radiation patterns [4]. Compared to the conventional Vivaldi antenna and antipodal Vivaldi antenna, balanced antipodal Vivaldi antenna (BAVA) is superior. The attractive features of BAVA such as low cross polarization, high gain, and low grating lobes make the antenna most preferable for the UWB applications [5]. In addition, these structures are compact in size and have symmetrical beamwidth which minimizes grating lobes at higher frequencies.

Several articles on the design and analysis of conventional Vivaldi antenna and balance antipodal balance Vivaldi antenna have been published in the literature. A low distortion and low loss balanced antipodal Vivaldi antenna for microwave imaging is reported in [6]. The antenna has an overall dimension of $80 \times 44 \times 9.3\,\mathrm{mm}^3$ designed on a Roger's RT/Duroid 6002 substrate with a relative permittivity of 2.94. The presented antenna operates over 2.4–18 GHz band and provides front-to-back ratio of 35%. However, the thermo plastic used in the design to assemble the layers is the primary source of measurement error. In [7], a balanced antipodal Vivaldi antenna ($79.9\,\mathrm{mm} \times 24\,\mathrm{mm} \times 0.508\,\mathrm{mm}$)

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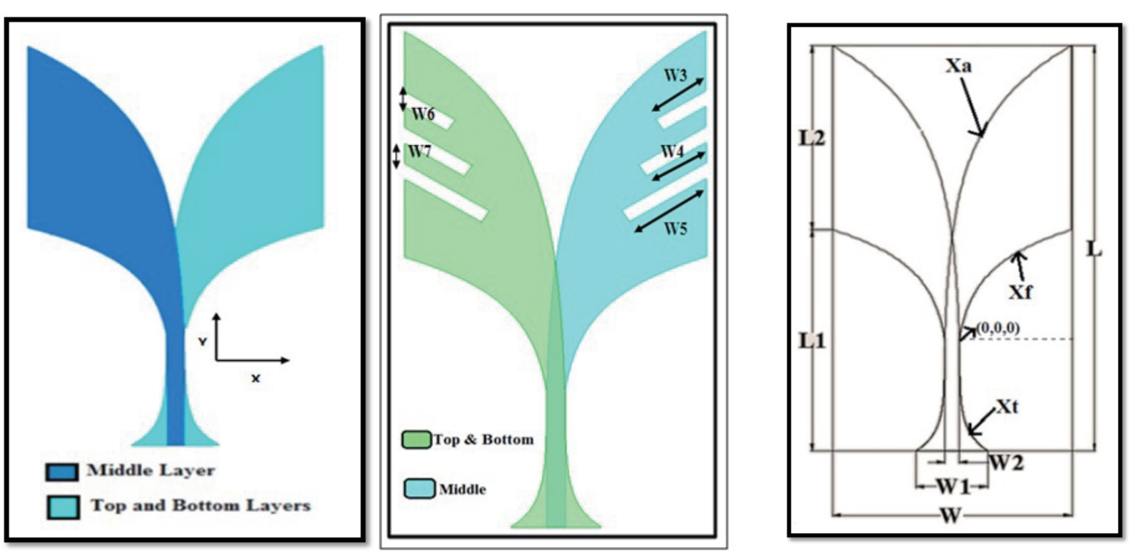
designed on a Roger's RT5880 substrate implementing asymmetric cutout between the metal radiating flares is proposed. In this design, the use of dual-scale slotted edges results in reduction in broadband sidelobe level which significantly improves the radiation characteristics at lower frequency. The antenna operates over 10–40 GHz with return loss less than −10 dB providing sufficient bandwidth. In [8], a compact antipodal Vivaldi antenna ($42 \times 36 \times 1.6\,\text{mm}^3$) printed on an FR4 substrate covering 3.7–18 GHz is presented. In this design, an improvement in the lower operating frequency is achieved by modifying the radiating fins structure. This antenna maintains realized gain of 1.8 dB–6.9 dB and efficiency of 54–82% in the whole operating bandwidth. The asymmetric ground plane and feeding structure limit the peak gain and maximum efficiency of the design. In [9], a tapered slot edge Vivaldi antenna ($36 \times 30 \times 1\,\text{mm}^3$) with a stepped structure is reported. The proposed antenna operates in the frequency range 2.35–11.6 GHz. Using this structure, a size reduction of 42.5% and impedance bandwidth in excess of 17% have been achieved without altering the physical size of the antenna. In [10], a compact and high gain elliptically tapered antipodal Vivaldi antenna for ultra wideband imaging system is presented. The antenna operates in the frequency range from 10 GHz to 40 GHz and is fabricated using a Roger's 4003C substrate with a dielectric constant of 3.38.

In this paper, a compact balanced antipodal Vivaldi antenna ($56 \times 28 \times 1.6\,\text{mm}^3$) with slotted edge is designed to improve the bandwidth at lower frequency. In particular, the antipodal Vivaldi antenna in [11] includes a lens and equal length rectangular slots at the flare edges for stable radiation patterns within the whole operational frequency band. A Palm Tree antipodal structure reported in [12] features an exponential slot edge at both the radiating fins to reduce the side lobe level and expands the low frequency limit. Furthermore, the antipodal structure presented in [13] is loaded with symmetrical elliptical grooves on two arms of the exponentially tapered slot patches along with metal vias to obtain the best adaptation at low frequencies. It shows that the antennas reported in [11–13] are antipodal Vivaldi antennas, while the proposed structure is a balanced antipodal Vivaldi antenna which has the advantage of high isolation and stable radiation characteristics due to the inclusion of an additional metallization layer. The main advantage of the proposed design is its small aperture width, typically 28 mm, which is rare to find in the previous design. Further, this antenna involves slanted rectangular slots of different lengths at the fin edges unlike the equal length slots used in the reports.



(a) (b)

Figure 1. (a) Conventional BAVA and BAVA with slotted edge, (b) antenna geometry.

2. ANTENNA DESIGN AND RESULT ANALYSIS

2.1. Antenna Design and Geometry

The proposed structure of the conventional BAVA (CBAVA) and the BAVA with slotted edges are depicted in Figure 1(a). As shown in the figure, the BAVA consists of two outer copper layers (top and bottom) and an inner layer (middle) supported by two dielectric substrates. Initially, an antipodal Vivaldi structure is designed using two copper layers printed on either side on the top substrate. Then, at the lower side of the bottom substrate, another copper layer is printed without etching the top surface. Further to achieve improved lower frequency performance, slotted edges are implemented on the radiating flares. The antenna is designed and fabricated on two FR4 ($\varepsilon_r = 4.4$) substrates each of thickness 1.6 mm. The antenna is fed using microstrip line feed. The detailed antenna geometry and dimensions are shown in Figure 1(b).

2.2. Parametric Study

2.2.1. Effects of Exponential Taper Rate on S_{11}

It has been revealed from the study that the taper rate (R) in the flare and aperture regions greatly affects the matching between the feed line and antenna slot. Hence, to realize optimal radiation characteristics and return loss, taper rate should be properly chosen. The variation in return loss with taper rate is plotted in Figure 2. Results show that the lower cut-off frequency is reduced form 6.8 GHz to 5 GHz, and the return loss is less than -10 dB at $R = 0.8$ over 5–20 GHz as compared to other values of taper rate. Therefore, the optimized value of taper rate is chosen to be 0.8 to realize large bandwidth and broadband characteristics.

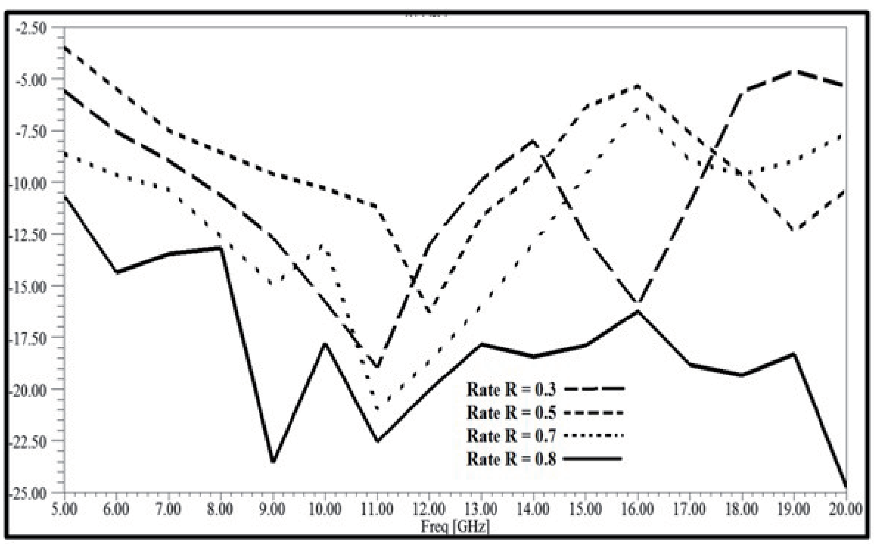


Figure 2. Return Loss plot at $R = 0.3$, 0.5, 0.7 and 0.8.

2.2.2. Effect of Offset Length, L_1 and Taper Length, L_2

Moreover, the offset length of the BAVA mainly depends on the taper rate and determines the impedance bandwidth of the antenna. Therefore, the effects of variation of the offset length on return loss are depicted in Figure 3. It is noted that the return loss is above -10 dB at lower values of L_1, typically at 26 mm and 28 mm. It is clear that the antenna bandwidth becomes standalone at the value of $L_1 = 30$ mm. Further, it is seen that the return loss becomes greater than -10 dB at $L_1 = 32$ mm. Further, the performance of the antenna is analyzed for different values of taper length, L_2. Figure 4

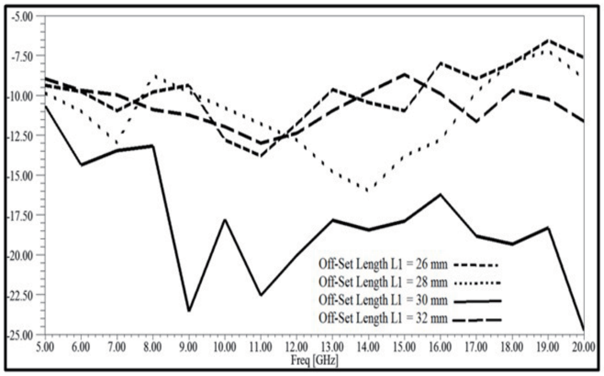


Figure 3. Effect of variation in L_1 on return loss.

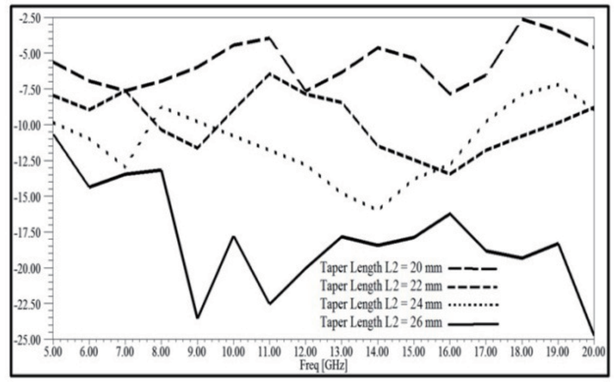


Figure 4. S_{11} for different taper length.

illustrates the return loss variation of the proposed antenna with taper length. It is seen that S_{11} is above -10 dB at $L_2 = 20$ mm, 22 mm, and 24 mm. It is evident that the optimized design is realized at $L_2 = 26$ mm that achieves return loss less than -10 dB with a bandwidth of 15 GHz from 5 GHz to 20 GHz.

From these parametric analyses, the optimized dimensions (in mm) of the antenna are (Figure 1(a) and (b)): Width, $W = 28$, Length, $L = 56$, Tapering Length, $L_1 = 26$, Off-Set Length, $L_2 = 30$, Ground Width, $W_1 = 10$, Stripline Width, $W_2 = 1.8$, Slot length, $W3 = 6$, $W4 = 8$, $W5 = 10$, Slot width, $W6 = 1$, $W7 = 1$.

3. FABRICATION AND EXPERIMENTATION

Figure 5 shows a prototype of the fabricated CBAVA and BAVA with slotted edge. The measurements are performed using Agilent E8364B vector network analyzer, and a 50 Ω cable is used as the antenna port. The whole structure is fabricated using FR4 dielectric substrates with dielectric constant 4.4 and thickness 1.6 mm.

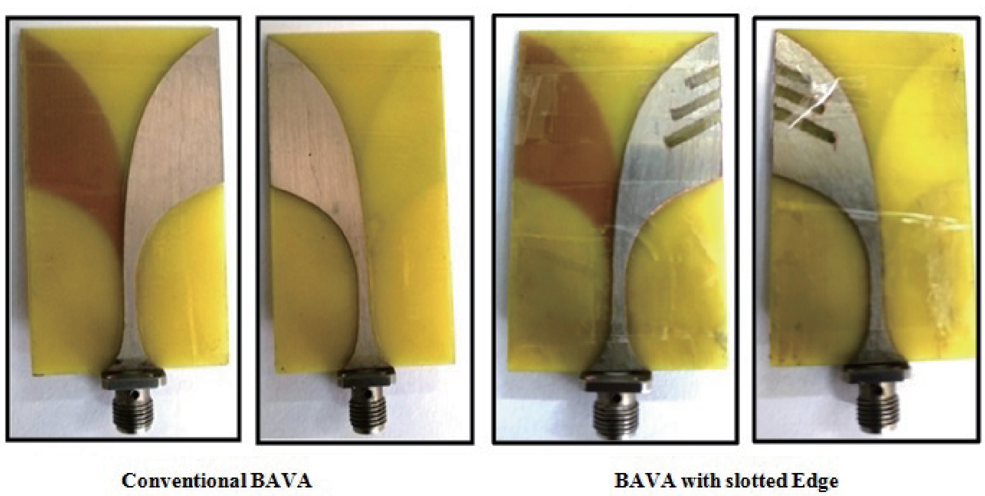


Figure 5. Prototype of fabricated antenna.

The S parameter of the fabricated prototype was measured to validate the results obtained through simulation. As indicated in Figure 6, the reflection coefficient is below -10 dB over the frequency band extending from 5 GHz to 20 GHz. Therefore, based on the measurement results, it is revealed

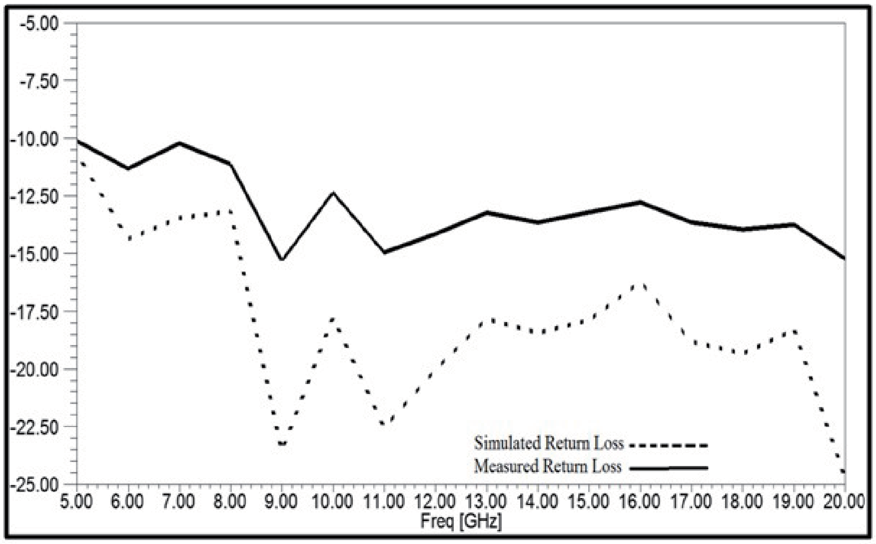


Figure 6. Measured and simulated return loss.

that the bandwidth of the antenna is 120%. There is an acceptable agreement between simulation and measurement results. However, the experienced deviations are attributed to the fabrication tolerances including plumbing loss, misalignment between the top and bottom metallization layers, and error caused by the SMA feed connector. In addition, in the simulation, the BAVA is excited by a microstripline feed line. Figure 7 and Figure 8 show the simulated and measured radiation patterns of the antenna at selected frequencies of 10 GHz and 18 GHz both in the E and H planes. The results reveal that the proposed antenna has directional radiation characteristics with the major lobe in the axial direction. It is noticed that at higher frequencies the antenna has good directivity and high front-to-back ratio. It is established that the far-field patterns of the antenna are directional and balanced, which is suitable for direction finding and electronic counter measure applications in the phased array system.

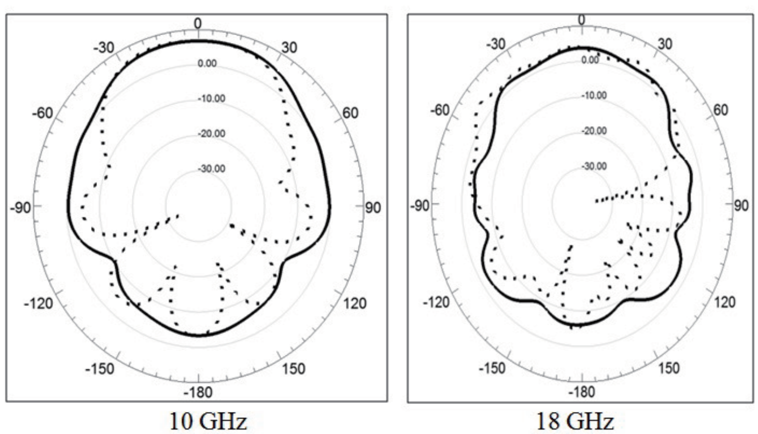


Figure 7. Simulated radiation patterns.

Figure 9 depicts the simulated and measured peak gains of the antenna. It is clear that the gain increases with frequency over the whole operating bandwidth. It is evident that the gain of the antenna increases from a value 2.6 dB at 5 GHz to 8 dB at 20 GHz. However, small deviations between the simulated and measured results may be due to fault in antenna fabrication and measurement error.

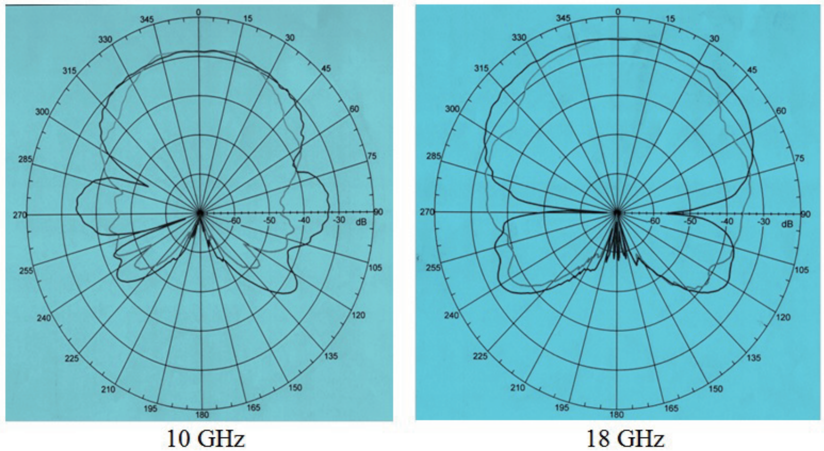


Figure 8. Measured radiation patterns.

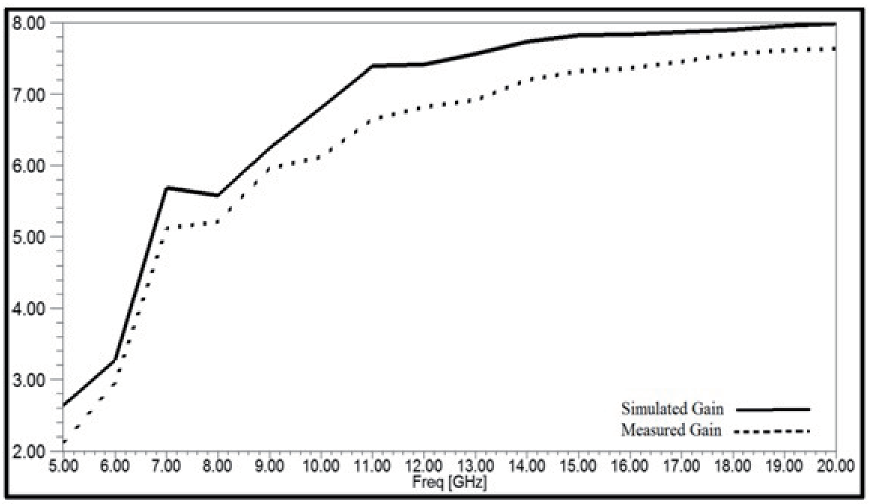


Figure 9. Simulated and measured realized gain.

3.1. Comparison of Antenna Performance

Table 1 lists the comparisons in terms of dimensions, operating frequency range and gain between the proposed design and antennas in the literature. Clearly, the proposed antenna has some distinct

Table 1. Comparison of performance.

Reference	Dimension (mm)	Operating Frequency (GHz)	Fractional Bandwidth	Gain (dB)
[6]	$80 \times 44 \times 9.3$	2.4–18	1 : 7.5	-
[8]	$42 \times 36 \times 1.6$	3.7–18	1 : 4.8	6.9
[9]	$36 \times 30 \times 1$	2.35–11.6	1 : 4.9	7
Proposed	$56 \times 28 \times 1.6$	5–20	1 : 4	8

advantages such as compact geometry, relatively wide bandwidth, and high gain. It is seen that the proposed antenna has an impedance bandwidth of 15 GHz which is comparable to the design reported in the literature. Furthermore, the specific feature of the design is its small aperture size which is 28 mm relative to the antennas in [6, 8, 9].

4. CONCLUSIONS

Microstripline fed balanced antipodal Vivaldi antenna implementing slots at flare edges has been presented. The proposed structure is compact in size and has a fractional bandwidth of 1 : 4 in the operational frequency band. The measured results show that it is able to cover the impedance bandwidth of 120% and peak gain of 8 dB on broadside at 20 GHz. Furthermore, the antenna has directional broadband radiation characteristics in both the principal planes. It is verified that there is an acceptable agreement between simulation and measurement results. The compact size and stable radiation characteristics in the whole band are the primary advantages of the present design. The average gain can be further improved by adding additional slots at the fin edges. Thus, the compactness, simple structure, and wide bandwidth of the proposed antenna have the potential to be used for advanced radar systems.

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