Parametric Analysis and Bandwidth Optimisation of Hybrid Linear-exponential Tapered Slot Vivaldi Antennas

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Abstract

This work presents an analysis of the effects of a hybrid linear-exponential tapered slot on the key properties of both the antipodal and co-planar Vivaldi antennas at low frequencies using parametric analysis and Nonlinear Sequential Programming optimisation. It was observed that the hybrid tapered slot can extend the lower frequency limit of the antipodal Vivaldi antenna however with slight deterioration of the gain and E-plane radiation pattern. On the other hand, the optimisation of the hybrid and conventional tapered slot co-planar Vivaldi antennas converged to antennas with the same performance results.

1 Introduction

The Vivaldi antenna is known for its compact size and good radiation properties over a wide frequency band [1]. Consequently, it is widely used in communication systems, ground and through-wall imaging, medical imaging and non-destructive testing of materials [2, 3, 4]. However, the Vivaldi antenna begins to lose its desirable properties, especially its compactness, as the operational frequency decreases. This is because the antenna radiates when the aperture width is greater or equal to half of the wavelength [1]. Therefore, the antenna becomes larger at lower frequencies. Furthermore, this large size makes it difficult to deploy the antenna for non-destructive investigation of structures in restricted and confined spaces encountered during post disaster operations and decommissioning of buildings. Consequently, the design of compact Vivladi antenna for low frequency operations has been the subject of various researches. [4, 5, 6].

In [7], a Chebyshev tapered outer curve was used to improve the lower frequency limit of a compact antipodal Vivaldi antenna. However, the reported antenna also used a hybrid linear-exponential tapered slot whose effects on the antenna properties were not examined. Therefore, this work aims to analyse the effects of this hybrid tapered slot on the properties of Vivaldi antennas in the lower frequencies using parametric analysis. This is in order to understand its mechanism of radiation and thus identify its strengths and limitations in the lower frequencies.

2 Methodology

The slots of both the antipodal and co-planar Vivaldi antennas were modelled with the conventional exponential taper and the hybrid linear-exponential taper and their performances were simulated and compared using Ansys HFSS. All the antennas were designed on 150 mm $\times$ 250 mm Rogers RO4003C substrate with thickness = 0.508 mm, relative permittivity (ϵ_r) = 3.55 and loss tangent = 0.0021. The chosen substrate width yields a theoretical lower frequency limit of 0.53 GHz.

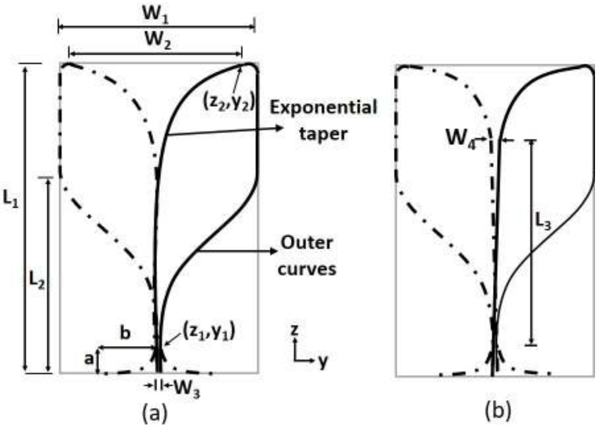

Fig. 1: (**a**) Exponential tapered slot antipodal Vivaldi antenna (ETAVA) (**b**) Linear-exponential tapered slot antipodal Vivaldi antenna (LETAVA)

The design of the exponential tapered slot antipodal Vivaldi antenna (ETAVA) is shown in Figure 1a. The equation for the exponential taper is given by Equation (1) where $P1$ is the opening rate of the exponential curve while (y_1, z_1) and (y_2, z_2) are the start and end points of the curves respectively [8]. The rounded edges (radius = 5 mm) at the end of the curves were introduced to eliminate the effects of diffraction due to sharp ends. A triangular taper [9] given by Equation (2) was chosen for the outer curves because of its low reflection loss. The length of the triangular taper L_2 is a fraction of the length L_1 of the exponential curve and is determined by $P2$. The ground plane to microstrip transition was implemented as an elliptical taper where a and b are the minor and major radii respectively. The width of the microstrip feed W_3 was calculated using Equation (3) to have an impedance of approximately 50 ohms [9]. The values for the other dimensions are as follows: L_1 = 230 mm, W_1 = 150 mm, W_2 = 140 mm, a = 20 mm and $b = (W_2 - W_3)/2$. The design of the hybrid linear-exponential tapered antipodal Vivaldi antenna (LETAVA) is shown in Figure 1b. It was obtained by replacing the lower part of the exponential taper with a linear taper whose length L_3 and opening width W_4 are given by Equation (4) where *P3* and *P4* are their respective controlling parameters.

$$y(z) = C_1 e^{P1\times z} + C_2 \qquad z_1 \le z \le z_2$$

where:

$$C_1 = \frac{y_2 - y_1}{e^{P1\times z_2} - e^{P1\times z_1}} \qquad (1)$$

$$C_2 = \frac{y_1 e^{P1\times z_2} - y_2 e^{P1\times z_1}}{e^{P1\times z_2} - e^{P1\times z_1}}$$

$$y(z) = \begin{cases} \frac{W_3}{2} e^{2(\frac{z}{L_2})^2 \ln \frac{W_1}{W_3}} & z_1 \le z \le \frac{L_2}{2} \\ \frac{W_3}{2} e^{(4\frac{z}{L_2} - 2(\frac{z}{L_2})^2 - 1)\ln \frac{W_1}{W_3}} & \frac{L_2}{2} \le z \le L_2 \end{cases} \qquad (2)$$

where:

$$L_2 = P2 \times L_1$$

$$\frac{W_3}{t} = \frac{2}{\pi}\left[A - 1 - \ln(2A-1) + \frac{\epsilon_r - 1}{2\epsilon_r}\left(\ln(A-1) + 0.39 - \frac{0.61}{\epsilon_r}\right)\right] \qquad (3)$$

where:

$$t = \text{substrate thickness and } A = \frac{377\pi}{2Z_0\sqrt{\epsilon_r}}$$

$$L_3 = P3 \times L_1 \quad \text{and} \quad W_4 = P4 \times W_3 \qquad (4)$$

The designs of the conventional exponential tapered slot co-planar Vivaldi antenna (ETCVA) and linear-exponential tapered slot co-planar Vivaldi antenna (LETCVA) are shown in Figures 2a and 2b respectively. The design of their tapered slots were obtained similarly to that of the antipodal Vivaldi antennas. Both co-planar Vivaldi antennas used the same radial stub microstrip to slotline feed whose design and reflection coefficient (S_{11}) are shown in Figures 2c and 2d respectively.

2.1 Antenna Optimisation

The main determinants of the performance of the antipodal Vivaldi antenna are the tapered slot curves and the outer curves (i.e. triangular taper) [10]. Therefore, *P1* and *P2* were chosen as the design parameters for the ETAVA. The design parameters

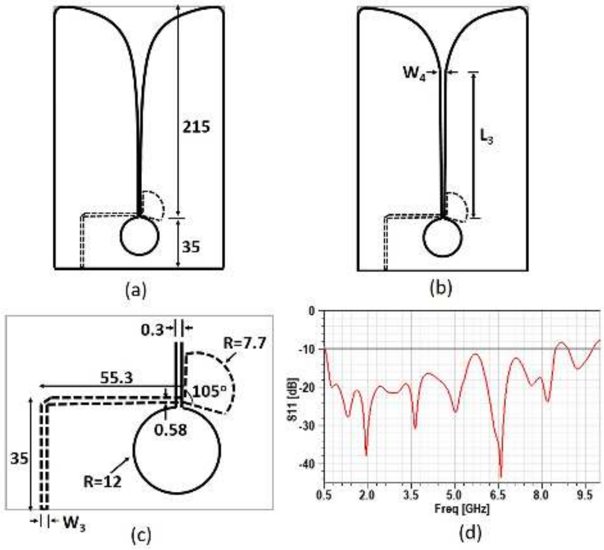

Fig. 2: (**a**) Exponential tapered slot co-planar Vivaldi antenna (ETCVA) (**b**) Linear-exponential tapered slot co-planar Vivaldi antenna (LETCVA) (**c**) Radial stub microstrip to slotline feed used by both co-planar Vivaldi antennas (**d**) Reflection coefficient of the radial stub microstrip to slotline feed *(All dimensions in mm)*

for the LETAVA are *P1*, *P2*, *P3* and *P4*. The only optimisable parameter for the ETCVA is *P1* while the design parameters for the LETCVA are *P1*, *P2* and *P3*. The starting points and search bounds for each parameter were obtained by performing a parameter sweep for each design parameter.

$$min : f = w_1\|E_{S_{11}}\|^2 + w_2\|E_{FB}\|^2 \qquad P_{i,min} \le P_i \le P_{i,max} \qquad (5)$$

Optimisation of the antennas was done using the Nonlinear Sequential Programming optimisation algorithm because of its suitability especially with finite element solvers such as Ansys HFSS [11]. The optimisation problem was formulated as shown in Equation (5). The cost function f to be minimised is the weighted sum of the squared errors in the reflection coefficient ($E_{S_{11}}$) and fractional bandwidth (E_{FB}). In other words, the algorithm tries to minimise the deviation of the reflection coefficient and fractional bandwidth (both of which are evaluated using the set of parameters P_i) from the specified goals. The goal of the fractional bandwidth was set to be greater or equal to 1.5. This is the theoretical fractional bandwidth of a Vivaldi antenna of similar aperture width with an upper frequency limit of 4 GHz. Fixing the upper frequency limit at a constant value of 4 GHz will force the optimiser to work towards reducing the lower frequency limit to achieve the fractional bandwidth goal. Furthermore, 4 GHz was chosen as a convenient point as the design parameter values generally showed good impedance matching above 4 GHz in all the antenna designs. The goal for the reflection coefficient was set to be less or equal to -10 dB across the achieved bandwidth in line with the widely accepted standard. Due to the importance of the reflection coefficient to be less than or equal to -10 dB across the achieved bandwidth, the weight w_1 of its objective function was given a value of 8. This is twice the weight w_2 of the objective function of the fractional bandwidth which was given a value of 4.

3 Results and Discussions

3.1 Antipodal Vivaldi Antennas

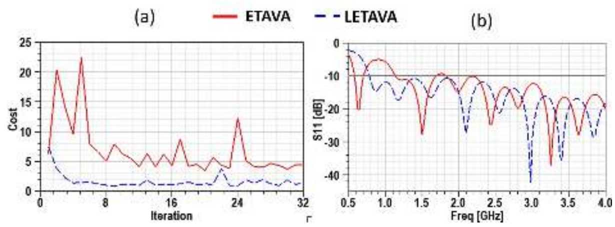

Fig. 3: (**a**) Evolution of the optimisation algorithm for both the ETAVA and LETAVA (**b**) Reflection coefficient of both the ETAVA and LETAVA

Figure **??** shows the evolution of the optimisation algorithm and the reflection coefficient for the optimal parameters for both the ETAVA and LETAVA. The cost in Figure **??**a is the value of the cost function at each iteration. It is a measure of the deviation from the specified goals where zero indicates that the goals have been achieved. The optimal parameter values for the ETAVA are *P1* = 0.04 and *P2* = 0.5 while those for the LETAVA are *P1* = 0.056, *P2* = 0.57, *P3* = 0.51 and *P4* = 1.02. It can be observed that the ETAVA is converging at a higher cost compared to the LETAVA even though both antennas have approximately the same cost at the first iteration. Consequently, the ETAVA has a higher lower frequency limit of 1.14 GHz with an error of 0.7 dB between 1.7 - 1.8 GHz. On the other hand, the LETAVA has lower frequency limit of 0.78 GHz which is about 30% lower than that of the ETAVA. The improvement in the lower frequency limit of the LETAVA is due to the additional degrees of freedom introduced by parameters *P3* and *P4* in the optimisation of the hybrid tapered slot. This enabled the LETAVA to have a longer radiating curve thereby allowed more currents to be available for radiation at lower frequencies. This can be observed in surface current distribution at 0.8 GHz for both antennas shown in Figure 4

The linear tapered slot antenna have been reported to have a higher gain compared to its exponential tapered slot counterpart [12]. Therefore, it was expected that the LETAVA should have a higher gain compared to the ETAVA because of the linear tapered portion of its slot. However, this was not the case as the LETAVA was observed to have an overall lower gain compared to the ETAVA (Figure 5a). Furthermore, a significant but momentary drop in the gain of the LETAVA was observed between 1.1 GHz and 1.5 GHz. Further analysis revealed that variation in the dimensions of the linear taper has little or no effect on the gain of the LETAVA (Figure 5b). On the other

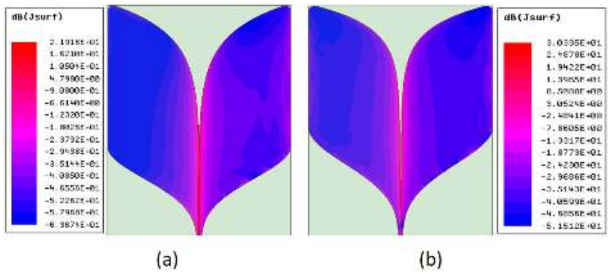

Fig. 4: Surface current distribution at 0.8 GHz (**a**) ETAVA (**b**) LETAVA

hand, the gain is very sensitive to the length of the outer curves (i.e. triangular taper) at lower frequencies as shown in Figure 5c. This is because the introduction of the outer curves in the antipodal Vivaldi antenna results in the reduction of the *effective* length of the antenna. This explains the sudden drop in the gain of the LETAVA between 1.1 GHz and 1.5 GHz because the optimal value of *P3* for the LETAVA is slightly higher than that for the ETAVA. Consequently, the LETAVA has a shorter effective length compared to the ETAVA. This means that the gain of the Vivaldi antenna depends more on the antenna length than the shape of the tapered slot.

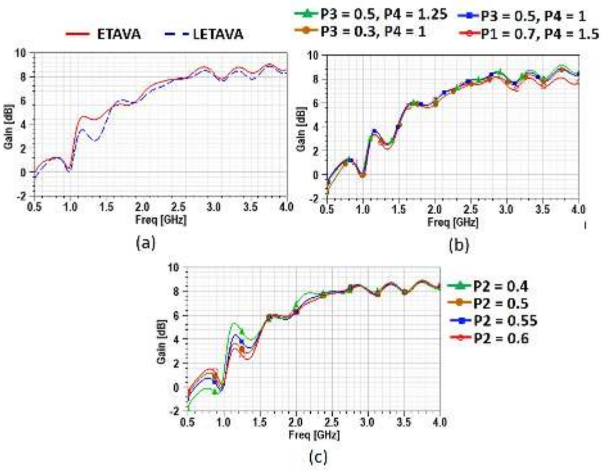

Fig. 5: (**a**) Gain of both the ETAVA and LETAVA (**b**) Gain of the LETAVA for different values of *P3* and *P4* (**c**) Gain of the LETAVA for different values of *P2*

The radiation pattern for both antennas are shown in Figure 6. It can be observed that both antennas have similar irregular E-plane patterns with tilted main beam and high sidelobes which is typical of the antipodal Vivaldi antenna. This irregular pattern is due to the asymmetric design of the top and bottom conductors which results in unbalanced E-fields. However, the introduction of the linear taper slightly increased the E-plane sidelobe levels of the LETAVA compared to the ETAVA. On the other hand, both antennas have a stable H-plane beam with the LETAVA having a consistently better H-plane half power beam width across the bandwidth. This is because the LETAVA have a longer narrow slot region compared to the ETAVA. Finally, these radiation pattern characteristics of both antennas are consistent with the E-plane beamwidth dependence on the aperture width and the H-plane beamwidth dependence on $1/\sqrt{L}$ (where L is the length of the slot) [12].

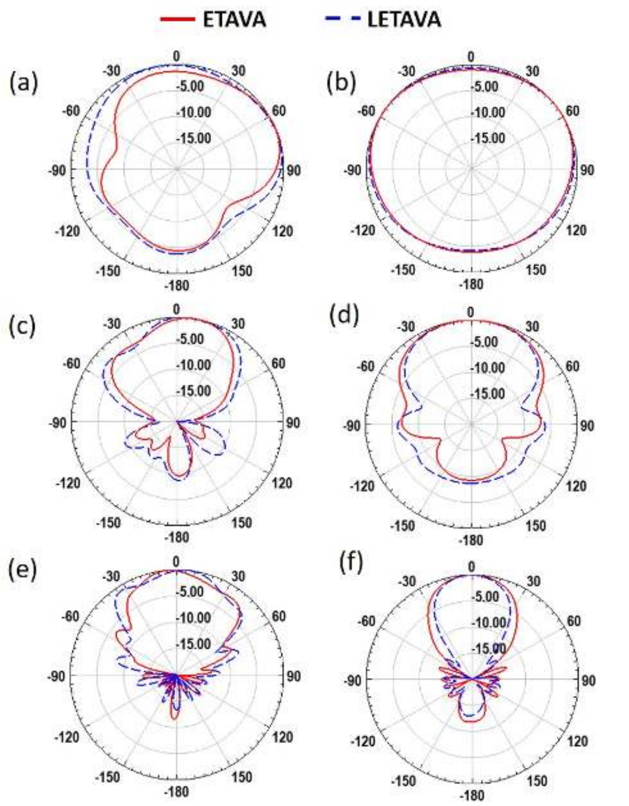

Fig. 6: Normalised radiation patterns for the ETAVA and LETAVA. Patterns at the top row are the E-plane patterns while the bottom row contain the corresponding H-plane patterns. (**a**) 0.8 GHz (**b**) 2 GHz (**c**) 3 GHz (**d**) 4 GHz

3.2 Co-planar Vivaldi Antennas

Figure 7a shows the evolution of the optimisation algorithm for both the LETCVA and ETCVA. It can be observed that both optimisation processes converged to the same cost. Consequently, a striking similarity can be observed between the optimal reflection coefficient curves of both antennas (Figure 7b). Furthermore, both the LETCVA and ETCVA achieved almost the same lower frequency limits of 0.76 GHz and 0.78 GHz respectively. This means that the optimisation of both designs converged to fundamentally the same antenna. This is further confirmed by the similarity in the gain curves as shown in Figure 7c. This convergence to the same antenna confirms that the main advantage of the linear taper in the LETAVA is its ability to reduce the overlap between the top and bottom conductors thereby enabling early opening of the slot region. This enables the exponential part of the radiation curve to be steeper resulting in an overall longer radiating curve. This advantage is not applicable in the LETCVA when compared to the ETCVA because the slot opens at the same point in both designs. Therefore, the hybrid linear-exponential tapered slot is more suitable in the design of compact antipodal Vivaldi antennas for low frequency applications.

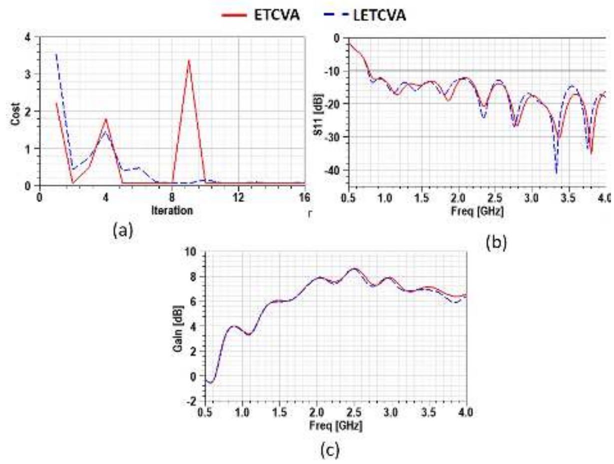

Fig. 7: (**a**) Evolution of the optimisation algorithm for both the ETCVA and LETCVA (**b**) Reflection coefficient of both the ETCVA and LETCVA (**c**) Gain of both the ETCVA and LETCVA

3.3 Measurements

Due to the relative similarity in the bandwidth of the designed antennas within the optimised frequencies, the LETCVA was chosen for fabrication as a representative design in order to validate the optimisation method. Furthermore, the relative regular and stable radiation pattern of the LETCVA compared to the LETAVA makes it more suitable for use in applications. The fabricated LETCVA and its measured reflection coefficient are shown in Figure 8a and Figure 8b respectively. The measurements were carried out using Rhode and Schwarz DST 200 anechoic chamber and ZVA40 vector network analyser. As can be observed, the measured reflection coefficient showed good impedance matching from 0.76 GHz to 9.65 GHz (i.e. 171% fractional bandwidth) and good correspondence with the simulated reflection coefficient within the optimised bandwidth. The disparity between the simulated and measured reflection coefficient above 4 GHz can be attributed to imperfections in the fabrication process and in the soldered connection between the SMA connector and the antenna because the effects of the imperfections become more pronounced at higher frequencies.

4 Conclusion

The effect of a hybrid linear-exponential tapered slot on the key properties of both the co-planar and antipodal Vivaldi antennas at lower frequencies have been investigated. The use of the hybrid linear-exponential tapered slot extended the lower frequency limit of the antipodal Vivaldi antenna by 30% in

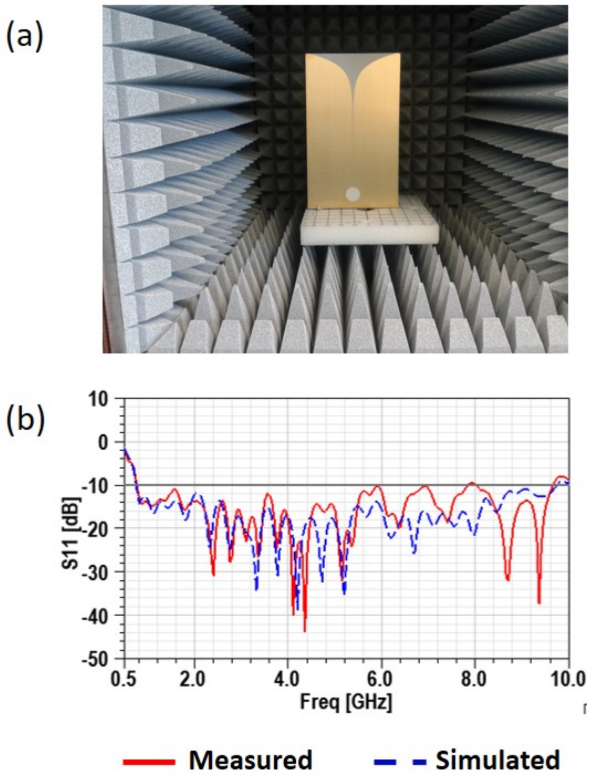

Fig. 8: (**a**) Fabricated LETCVA. (**b**) Measured and simulated reflection coefficient of the LETCVA

comparison to conventional exponential tapered slot. This was because the combination of the linear and exponential tapered slot enabled early opening of the slot region resulting in longer radiating curves. However, this also resulted in slight deterioration of the far field properties. Furthermore, the hybrid tapered slot did not result in any significant change in the antenna properties when applied to the co-planar Vivaldi antenna. In addition, it was also observed that the gain of the Vivaldi antenna depends more on the effective length than the shape of the tapered slot and that the lower frequency limit is independent of the type of Vivaldi antenna. These and other findings will provide additional valuable information in the appropriate choice of techniques for improving the low frequency operation of the Vivaldi antenna.

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