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A Parametric Analysis & Design of All Metal Vivaldi Antenna Covering 3.0–18 GHz for DF and Phased Array Applications

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Abstract—Ultra-wideband antennas covering 1–18 GHz are required for Direction Finding (DF) and phased array applications in electronic warfare and communication systems. Several antennas such as Archimedean spirals, Log periodics, Ridged horns have been extensively used for ESM-DF applications. In this paper an all metal Vivaldi antenna covering 3–18 GHz is designed using HFSS software, and hardware has been realized. A measured VSWR of less than 2.5 over 3–18 GHz is obtained. Radiation patterns are satisfactory both in simulations and measurements. There is fairly good agreement between the two. Further parametric studies are carried out on the single antenna with side and back walls, and this design is optimized for VSWR of less than 2.5 over the band. This antenna is used in a linear array of 8 elements. For this array in simulations, scanned patterns devoid of grating lobes are obtained from 3.0 GHz to 9.0 GHz, and results are presented.

1. INTRODUCTION

In ESM systems, direction finding is an important parameter estimated through a multi antenna system configured in a circle in amplitude comparison technique. In this technique usually 4, 8, 12 antennas are used to cover 360° in azimuth and approximately $\pm 30°$–$\pm 50°$ in elevation [1]. Log periodic antennas, Archimedean spirals, Log spirals, Ridged horns covering 2–18 GHz have been used in several applications [2–4]. DF systems cover 1–18 GHz usually in four bands namely 1–2 GHz, 3–4 GHz, 4–8 GHz, and 8–18 GHz. This can also be realized in a single band or in two bands.

Tapered slot antennas and their variants have been used extensively in recent times for communications and EW applications covering frequency range of 1–18 GHz. For example, Nurad and MIT jointly developed 3 : 1 and 9 : 1 bandwidth dual polarized planar phased array using printed Vivaldi antennas [5]. In this paper, design and dimensional details are not reported. In a different paper, 5 : 1 bandwidth Vivaldi antenna array for radio astronomy applications is reported [6]. Further, a phased array with 3 : 1 bandwidth operating over 6–18 GHz and scanning to $\pm 45°$ has also been reported [7]. An antipodal Vivaldi antenna with elliptical patch with a parasitic element and an aperture size of 66 mm covering 6–21 GHz is available in literature [8]. An ultra-wideband small aperture tapered slot phased array antenna operating over 5.6–20 GHz with a VSWR of less than 2.5 can also be seen in literature [9]. A compact antipodal Vivaldi antenna with rectangular slots with shaping of flare design over 6–18 GHz is also reported in the literature [10]. A bandwidth of 6–18 GHz is reported with a modified Vivaldi antenna [11]. These are printed antennas with much of fabrication complexity and need to solder adjacent elements in a dual polarized array.

To overcome difficulties in fabrication and realization of printed array antennas, all metal Vivaldi antennas have been designed and realized in recent times. An ultra-wideband flared notch array radiator with 12 : 1 bandwidth and scanning to 45°, with a VSWR of less than 2.5 covering a bandwidth of 700 MHz–9 GHz has been reported [12]. A dual polarized 2–18 GHz Vivaldi array for airborne radar

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for snow surveillance is also reported [13]. An all metal phased array antenna having a bandwidth of 6–12 GHz with a VSWR of less than 2.5 and scanning to 45° is available. An ultra wideband loss less cavity backed Vivaldi 3×4 array antenna has been analyzed and implemented with a VSWR of less than 2.5 from 1.5–7.5 GHz [14].

It can be seen from the above, the all metal Vivaldi antennas available in literature are all designed and realized in the form of planar arrays. Single Vivaldi antenna design for isolated element is seldom reported. Though some dimensional details have been given in some cases, detailed parametric studies have not been reported in literature. Also radiation patterns of single isolated antenna are not available.

In this paper, detailed parametric studies are carried out, and the effect on return loss is studied and analyzed. All metal Vivaldi antenna covering 1–18 GHz in a single band is ideally suited for DF applications. Keeping this in view, an all metal Vivaldi antenna covering 3.0–18 GHz is designed and implemented. Parametric studies are carried out for optimizing the design to obtain a return loss of less than -7.5 dB (VSWR < 2.5) over the band.

This paper is organized in six sections. Section 1 Introduction, Section 2 Antenna geometry, Section 3 Parametric studies, Section 4 Simulated results, Section 5 Measured results, and Section 6 Conclusions are given.

2. ANTENNA GEOMETRY

The antenna geometry is shown in Fig. 1.

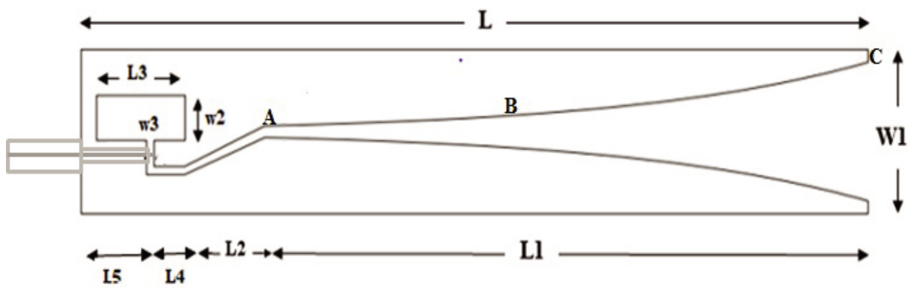


Figure 1. Antenna geometry line drawing.

The antenna consists of a tapered slot line shown as a curve ABC in Fig. 1. The tapered slot line is loaded by a rectangular cavity of length L_3 and width w_2, for broadband matching. The slot line is excited by a coaxial line of length L_5 with the center conductor joined to the other end of the slot line as shown in Fig. 1. For mechanical rigidity, side wall and back wall are included. The aperture size W_1 of the single antenna is 20 mm, and including the side walls it is 24 mm. Simulations have been carried out with back wall and side walls.

The tapered slot line portion is designed with the following standard equations. The line equation of opening rate (R) for points P_1 (y_1, y_2) and P_2 (z_1, z_2) (start and end points on the exponential curve) is given by [15],

$$Y = C_1 e^{RX} + C_2 \tag{1}$$

where

$$C_1 = (y_2 - y_1) \,/\, \left(e_2^{RZ} - e_1^{RZ}\right) \tag{2}$$

$$C_2 = \left(y_1 e_2^{RZ} - y_2 e_1^{RZ}\right) \,/\, \left(e_2^{RZ} - e_1^{RZ}\right) \tag{3}$$

where C_1, C_2 are constants, and R is the opening rate of the exponential taper.

3. PARAMETRIC ANALYSIS

The following are the various dimensional parameters which are found to affect the VSWR Bandwidth.

- Antenna length 'L'
- Rectangular cavity Length 'L_2'
- Rectangular cavity width 'W_2'
- Growth rate of the tapered portion 'R'
- Position of the feed w.r.t cavity 'EF' (Fig. 5)
- Effect of back and side walls

The above parameters are varied with HFSS software [16] to obtain a return loss of less than -7.5 dB over 3.0–18 GHz. In the following paragraphs, the variation of return loss w.r.t the above parameters is analyzed.

3.1. Antenna Length 'L'

The antenna length 'L' is varied from 127–140 mm, and return loss is as shown in Fig. 2.

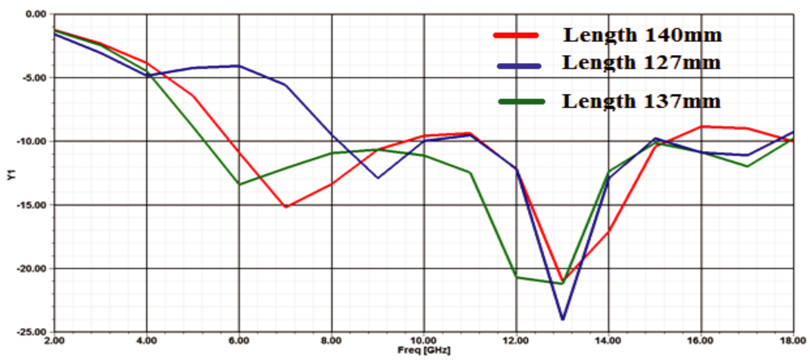


Figure 2. Comparison of return loss by varying antenna length.

— Blue color plot is the return loss plot for an antenna length of 127 mm. The return loss is observed to be below -7.5 dB from 8.3 to 18 GHz.
— Green color plot is the return loss plot for an antenna length of 137 mm. The return loss is observed to be below -7.5 dB from 3.0 to 18 GHz.
— Red color plot is the return loss plot for an antenna length of 140 mm. The return loss is observed to be below -7.5 dB from 5 to 18 GHz.

From the above it can be seen that the antenna length has significant effect on bandwidth, and the optimum length is 137 mm.

3.2. Rectangular Cavity Length 'L_2'

The rectangular cavity length L_2 is varied from 12.1 mm to 14.1 mm, and return loss is as shown in Fig. 3.

From the above it can be seen that the antenna cavity length has no effect on the band width though at higher frequencies it has some effect.

3.3. Rectangular Cavity Width 'w_2'

The rectangular cavity width W_2 is varied from 6.6 mm to 7.6 mm, and return loss is as shown in Fig. 4.

From the above it can be seen that the antenna cavity width has no significant effect on the achievable bandwidth.

3.4. Position of the Feed

The coaxial feed is shown as in Fig. 5. The position of feed 'F' is changed, and return loss variation is noted. The length 'EG' is conveniently chosen to incorporate the coaxial feed without much of

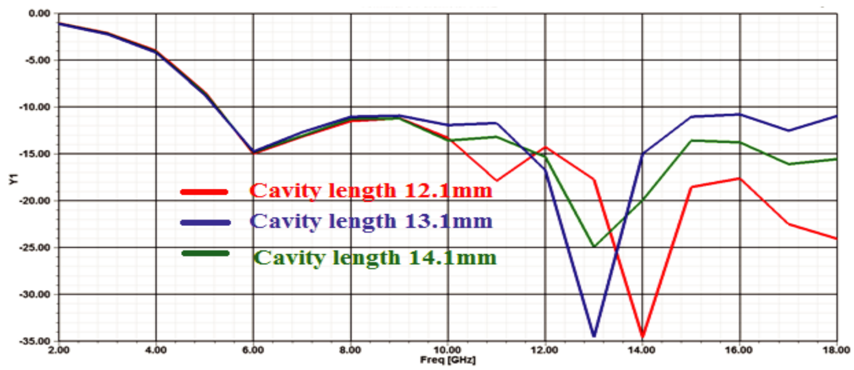


Figure 3. Comparison of return loss by varying cavity length.

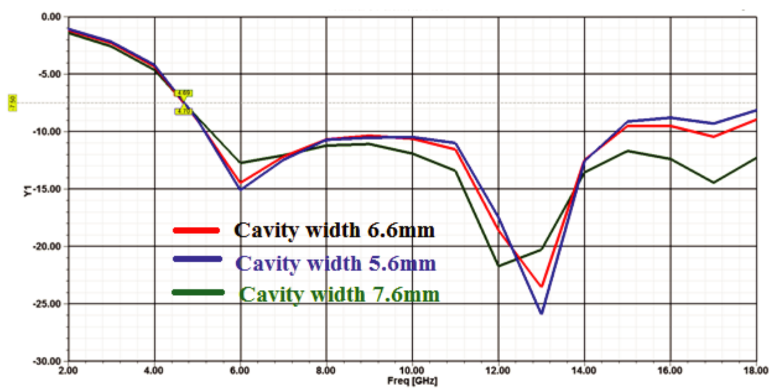


Figure 4. Comparison of return loss vs. cavity width.

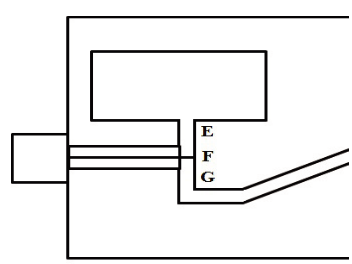


Figure 5. Sketch of feed position.

fabrication criticality. Initially position of the feed is taken as the mid point of line 'EG'. EF is varied from 3.4 to 3.6 mm, and effect of this position on the return loss is studied and plotted in Fig. 6.

From the above it can be seen that there is significant variation in bandwidth w.r.t. feed position. Feed position with $EF = 3.6$ mm results in the largest bandwidth.

3.5. Growth Rate of the Tapered Portion

The growth rate of the tapered portion is varied from 0.76 mm to 0.96 mm, and return loss obtained is as shown in Fig. 7.

From the above it is evident that the antenna growth rate has significant effect on return loss at higher end of the band. Band width is unaffected considering -7.5 dB return loss as the maximum allowed.

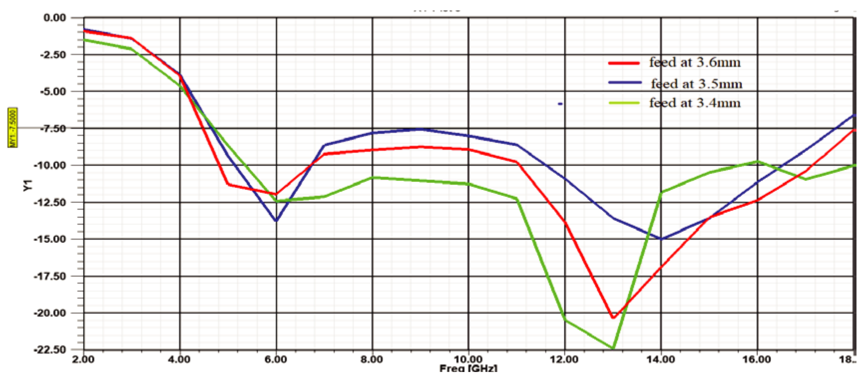


Figure 6. Return loss with different feed positions.

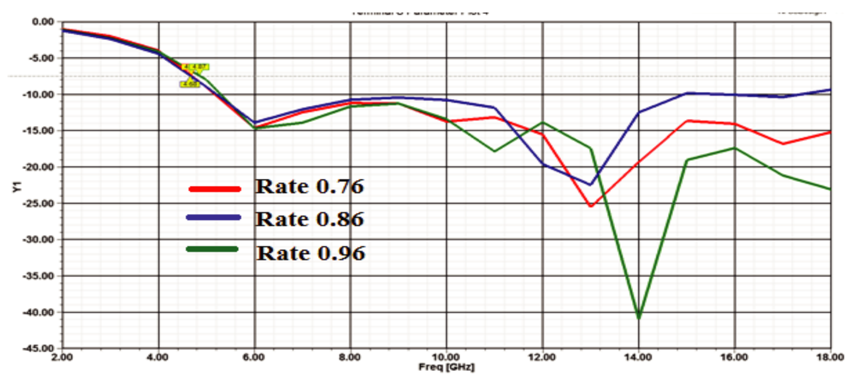


Figure 7. Return loss with exponential growth rate.

3.6. Effect of Back Wall and Side Walls

The design without side walls is taken as reference, and then its return loss is compared with the design including side walls of width 2.0 mm on either side and on all sides of antenna except at the radiating part of the antenna. Back wall is also included in this study. The results obtained with and without sidewalls are shown in Fig. 8.

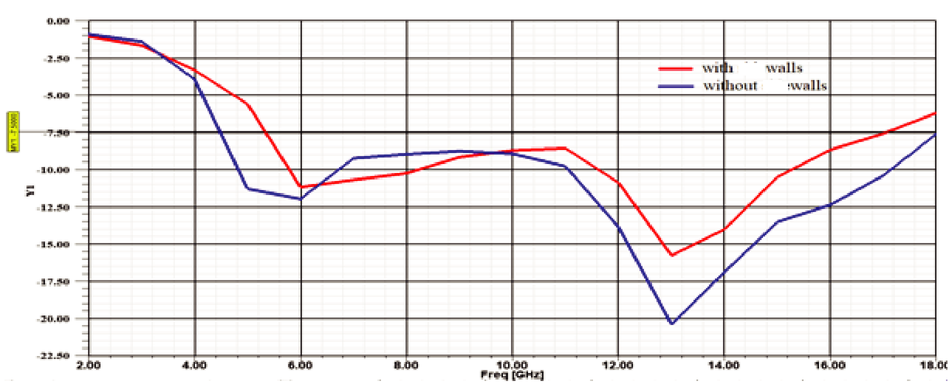


Figure 8. Comparison of return loss with and without walls.

From the plot it is observed that

— For Red color plot representing the antenna design with side and back walls, the Return loss is below −7.5 dB over 5.3–18 GHz.

— For Blue color plot representing the antenna design without walls, the Return loss is below −7.5 dB over 3.0–18 GHz.

From the above it is evident that the antenna without side walls results has maximum bandwidth. The optimum dimensions for obtaining maximum bandwidth are given in Table 1.

Table 1. Optimum antenna dimensions.

S. No.	parameter	Dimensions in mm
1.	L	140
2.	$L1$	105
3.	$L2$	13.1
4.	$L3$	7.3
5.	$L4$	10.7
6.	$L5$	5.8
7.	$W1$	24
8.	$W2$	6.6
9.	$W3$	2.0
10.	R	0.86

4. SIMULATION RESULTS

The design has been optimized with the dimensions obtained in Table 1. Final return loss is given in Fig. 9.

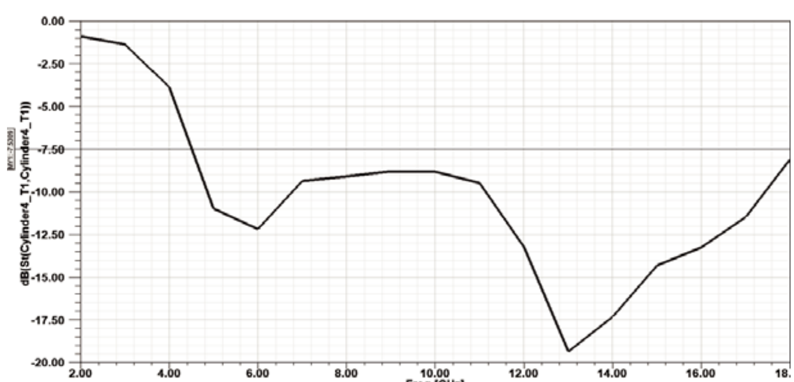


Figure 9. Optimized return loss.

4.1. Return Loss

The return loss of the all-metal antenna without walls is below −7.5 dB from 4.6 to 18 GHz, and it is −22.5 dB at 13 GHz.

4.2. Radiation Patterns

Radiation patterns are computed in E and H planes. The patterns from 4 to 18 GHz are shown in Figs. 10(a)–10(d). (Red line — H plane; Blue line — E plane).

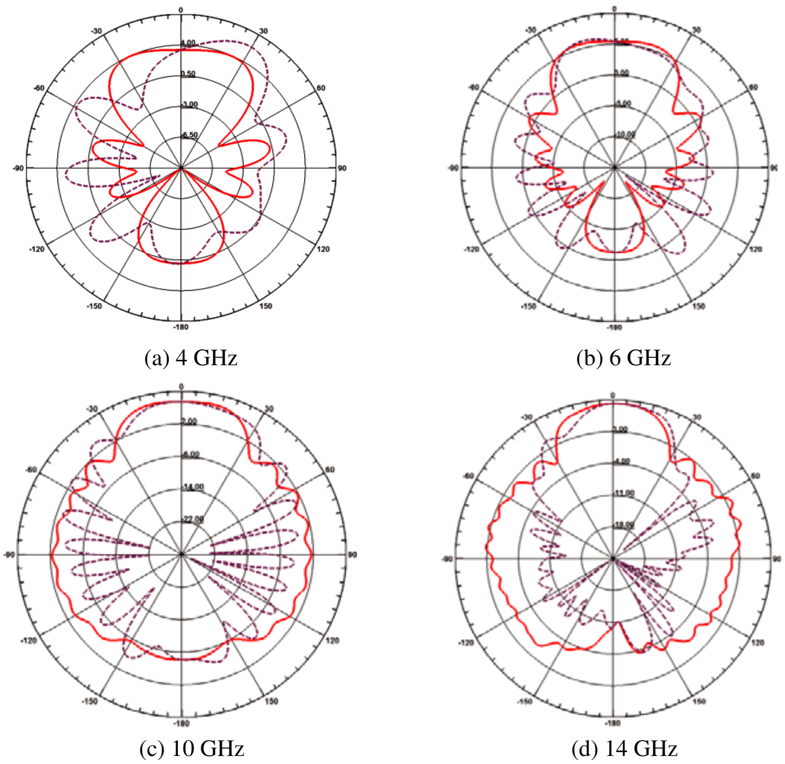


Figure 10. Radiation patterns of the antenna.

4.3. Gain

Gain values are computed over 4.0 GHz to 18 GHz and plotted in Fig. 11.

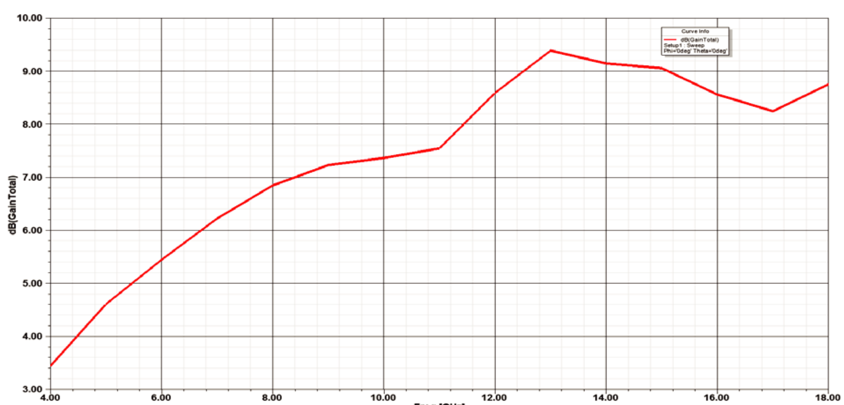
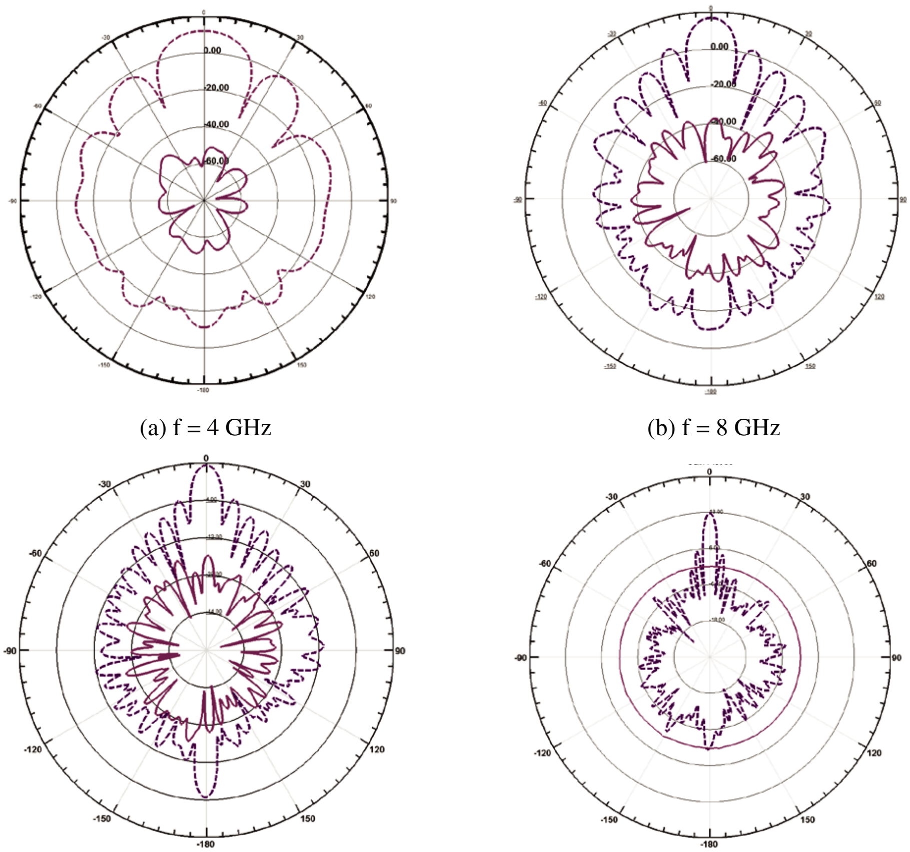


Figure 11. Frequency vs. gain.

Gain varies as 3.5 dB at 4.0 GHz, 9.3 dB at 13 GHz, and 8.7 dB at 18 GHz.

4.4. Co and Cross Polarization Patterns

Co and cross polarization patterns are computed and shown in Figs. 12(a) to 12(d). Dotted line represents co-polarization and solid line represents cross-polarization patterns.



(a) f = 4 GHz (b) f = 8 GHz

(c) f = 12 GHz (d) f = 18 GHz

Figure 12. Co & cross polarization patterns.

It can be seen that the cross polarization computed in simulations on bore sight is better than 40 dB over the entire band. At 18 GHz, the cross polarization pattern is not seen as it is better than 50 dB and appears as a dot.

4.5. Linear Phased Array

A linear array with the all metal Vivaldi antenna as an element with 8 elements has been simulated using HFSS software. The HFSS model of the array is shown in Fig. 13. The array has both the side walls and back wall.

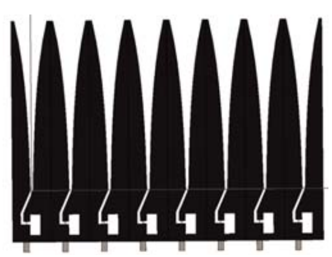


Figure 13. Linear array all metal Vivaldi.

Maximum scan angle without appearance of grating lobes depends upon the spacing between elements in terms of wavelength given by the standard relation

$$d/\lambda = 1/(1 + |\sin \Theta_S|) \tag{4}$$

where,

d — the spacing between elements;

Θ_S — the maximum scan angle.

Equation (4) is plotted for the spacing of 2.4 cm between elements for maximum scan angle obtainable w.r.t. frequency as shown in Fig. 14.

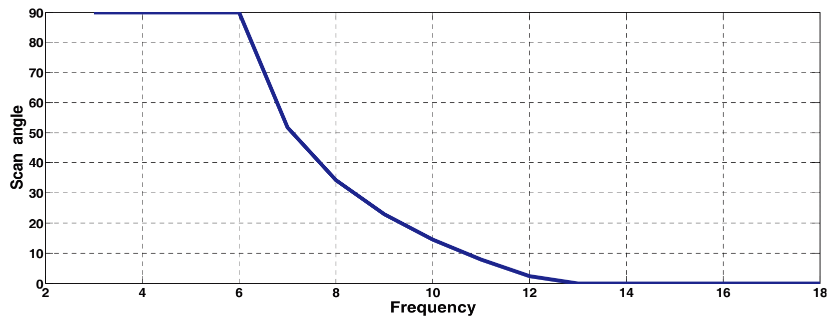
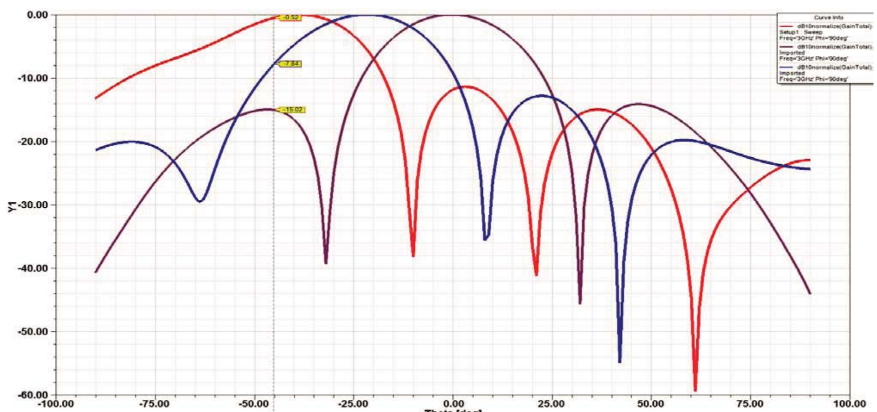
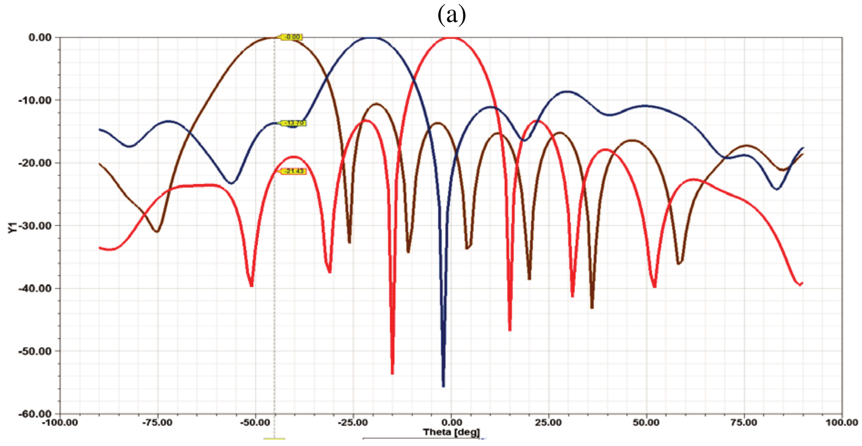


Figure 14. Frequency vs. scan angle for a spacing between elements of 2.4 cm.

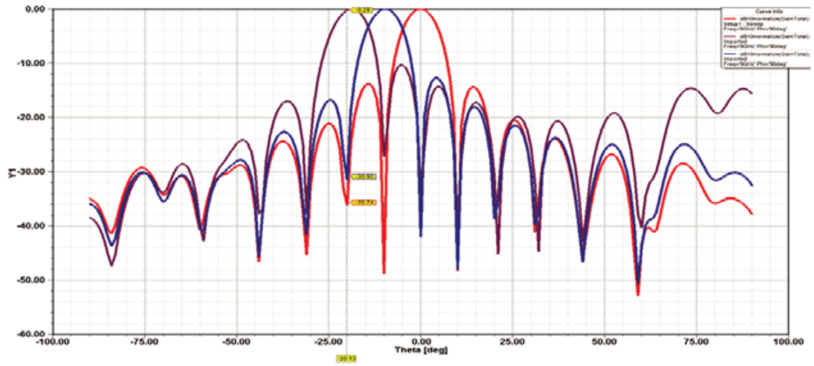
It can be seen from the above plot that for the chosen spacing, scanning without grating lobes is possible from 3.0 to 6.0 GHz up to 90°, and the maximum scanning limit comes down nearly exponentially. At 9.0 GHz, a maximum limit of only 20° is possible in E plane (the plane of the array). The scanned patterns are shown in Figs. 15(a)–15(c).



(a)



(b)



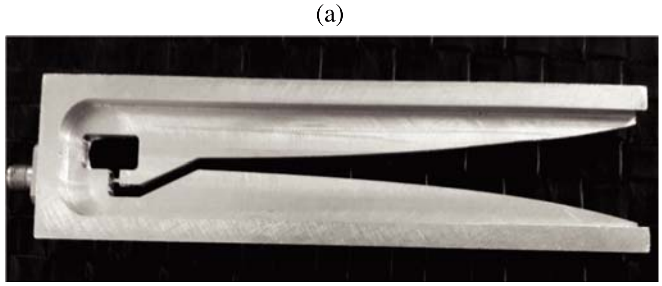
(c)

Figure 15. (a) 3 GHz (0°, 22.5°, 45°). (b) 6 GHz (0°, 22.5°, 45°). (c) 9 GHz (0°, 10°, 20°).

5. EXPERIMENTAL RESULTS

The antennas are fabricated with the optimized dimensions given in Table 1. Aluminum metal is used, and wire cut technology is used for machining. The fabricated antennas with and without walls are shown in Figs. 16(a)–16(b).

(a)



(b)

Figure 16. (a) The All-metal Vivaldi antenna. (b) The all-metal Vivaldi antenna with side and back walls.

5.1. VSWR

Measured antenna VSWR is less than 2.5 VSWR (Return loss less than −7.5 dB) over 3.0–18.0 GHz, as shown in Fig. 17.

5.2. Radiation Patterns

The measured radiation patterns at different frequencies are shown in Figs. 18(a)–18(e). Chain line represents H plane, and solid line represents E plane.

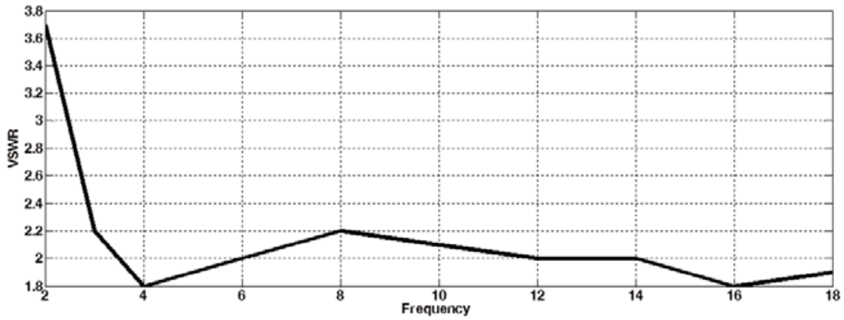
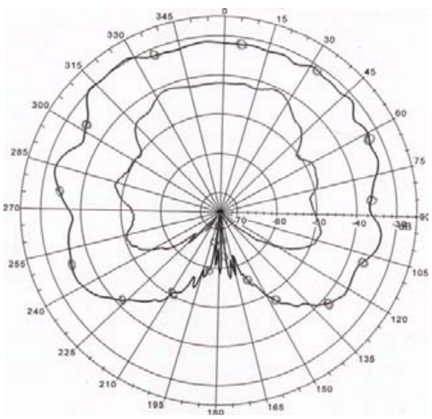
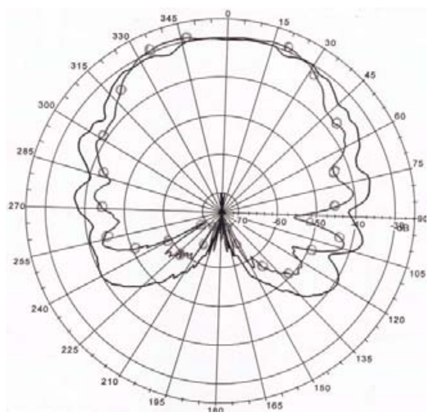


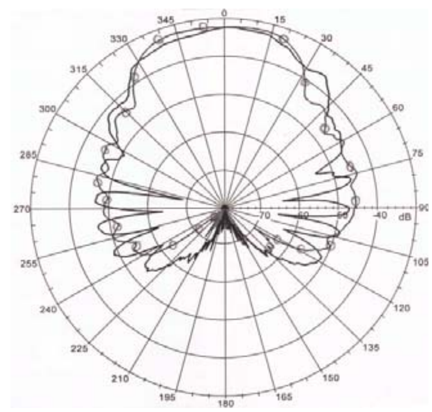
Figure 17. Measured VSWR plot.



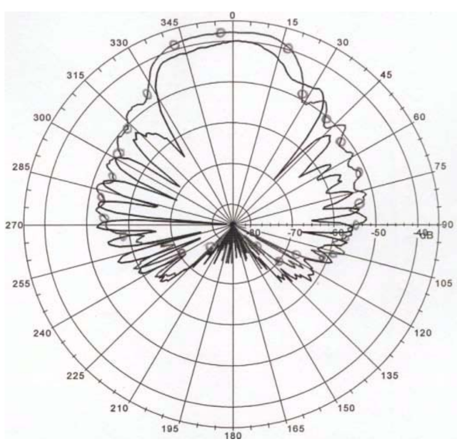
(a) 4 GHz



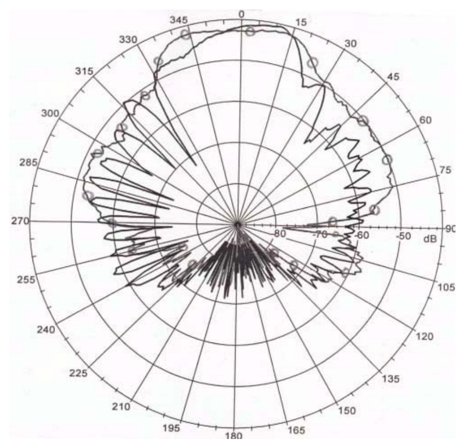
(b) 6 GH



(c) 10 GHz



(d) 14 GHz



(e) 18 GHz

Figure 18. Measured radiation patterns.

6. CONCLUSION

All metal Vivaldi antenna is considered as an alternative antenna for the proposed DF system. In amplitude comparison antenna DF systems log periodics, Archimedean spirals, ridged horns have been largely used as antenna elements. All metal Vivaldi antenna is an elegant alternative to these antennas having advantages of lesser weight and fabrication complexity specifically for ship board installations. Keeping these advantages in view, an all metal Vivaldi antenna has been designed using HFSS software, and a bandwidth of 4.6–18 GHz is obtained with a return loss of −7.5 dB. In simulations, it is noted that the gain varies from 3.4 dB at 3.0 GHz to 8.7 dB at 18 GHz. The desig is optimized to realize largest bandwidth through parametric studies and analysis. The optimized antenna is realized in hardware. A return loss of −7.5 dB over 3.0 GHz–18 GHz is obtained in measurements. Radiation patterns in simulations and measurements are satisfactory. Cross polarization ratio obtained in HFSS simulations is better than 40 dB. The antenna can be used for direction finding applications both in amplitude and phase comparison systems. Further a linear array consisting of 8 all aluminum Vivaldi antennas is modeled in HFSS, and scanned patters are obtained which are quite satisfactory. Scanning limits of this array are also discussed.

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