International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 4 (2015) pp. 10579-10593

http://www.ripublication.com

Design and Analysis of Vivaldi Antenna Array forX-Band Airborne Radar Applications

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Abstract

A Vivaldi antenna with stripline feed has been designed for X-band airborne radar applications. The main aim is analysis of antenna elements suitable for widescan active phased array antenna.The choice of a dielectric substrate is one of the most important aspects of the design of a Vivaldi antenna for wideband applications. Two different dielectric substrates are taken for fabrication of Vivaldi antenna. It has been proven that, if the dielectric permittivity and substrate thickness is increased, the bandwidth, gain, and beamwidth will be reduced. Further the return loss is higher for higher permittivity substrate which decreases the operating frequency. We first fabricated the designed Vivaldi antenna using high permittivity ($\varepsilon_r = 4.4$) substrate with obtained bandwidth of 800MHz in X-band frequency. Secondly, we fabricated Vivaldi antenna using lower permittivity ($\varepsilon_r = 2.2$) substrate with obtained bandwidth of more than 1GHz operating frequency in X-band with high gain of 4dB and 3dB beam width greater than $\pm 60^o$ in both H-plane and E-plane. Design of linear array of 9-elements is presented and simulated return loss for center element is achieved less than -10dB including mutual coupling effects. The planar array ensures a gain of 23.6dB with low SLL of 13dB and beamwidth as narrow as 10 degrees in E and H-planes. The designed structure and phased array antenna is expected to find applications in military aircrafts.

Keywords. Vivaldi antenna,Tapered slot antenna, stripline to slotlinetransition, sidelobe level, permittivity, Dielectricsubstrate, bandwidth, beamwidth, gain.

Introduction

The use of tapered slot antenna (TSA), often called notch or Vivaldi antenna, for wide-band/widescan phased arrays was proposed more than two decades ago [1],[2].

These arrays offer one of the best opportunities for realizing wide-bandwidth, wide-scanning phased arrays.This paper attempts to design TSA by providing information about achievable performance and relationships between specific antenna parameters and performance using the full wave simulation tool high frequency structure simulator (HFSS). A parameter study of tapered slot antenna shows the key features that affect the wide-band and wide-scan performance of this antenna. The overall performance can be optimized by judiciously choosing a combination of parameters. The design guideline is introduced, and the antenna parameters including Voltage Standing Wave Ratio (VSWR), radiation patterns and gain are investigated.

Phased arrays have been required to operate over wide bandwidths and wide scan angle to support multifunctionoperation in both telecommunication and radarapplications [3], [4]. Phased array antennas are attractive for applications that require rapid scanning of the beam ormultiple simultaneous beams [5],[6]. In response to that need,a wideband widescan tapered slot antennawith striplinefeed network has been designed. This antenna can operate from 8 to 12 GHz and scan angle up to $\pm 60^o$. The simulation results are shown to certificate the performance of the proposed antenna.Vivaldi antenna gives significant advantages of efficiency, high gain, wide bandwidth and simple geometry [7].

A tapered slot antenna has a slotline flare from a small gap(50Ω) to a large opening(377Ω), matching to free space wave impedance. TSA is larger than a half wavelength to achieve the desired performance[8]. TSAs have moderately high directivity and narrow beamwidth because of the travelling wave properties and almost symmetric E-plane and H-plane radiation patterns over a wide frequency band as long as antenna parameters like shape, total length, dielectric thickness and dielectric constant are chosen properly. TSA has the unique characteristics of symmetrical patterns in two planes, high gain in addition to having wide bandwidth characteristics in termsof radiation performance and impedance characteristics [9].

This paper describes design of a compact, wide band and wide beam dual layered exponentially tapered slot antenna by a striplinefeed. It is constructed from stripline fed tapered slotline elements. This antenna can electronically over wide scan volume, operate in a wide frequency bandwidth and radiate in all desired polarizations. This paper attempts to design Vivaldi antenna by providing information about achievable performance and relationships between specific antenna parameters and performance. These results should improve confidence in proposed antenna designs and reduce the numerical and empirical iterations needed to optimize antenna for airborne radar applications. The primary advantage of this type of antenna is a reasonably high gain (4-7 dB), wide bandwidth (8-12 GHz), low sidelobes, good directivity and ease of fabrication. The complete design and optimization of the antenna has been done using a general purpose commercial finite element based electromagnetic simulator HFSS. The opposite side of the substrate includes a microstrip feed and cross over transition that excites a rectangular cavity on the slot side. The energy from this cavity is transferred to the slotline taper.The focus of this work is on the design of the slot taper, to maximize power transformation and minimize reflection. For exponential tapers, trial and error approaches have been used for taper design in order to determine the exponential opening rate.

The choice of a dielectric substrate is one of the most important aspects of the design of a Vivaldi antenna. The key characteristics of a substrate material are its dielectric constant, loss tangent, and the thickness of the dielectric of the copper cladding. The insertion loss of the antenna depends on the dielectric constant, loss tangent, and thickness of the substrate used. If the substrate thickness is increased, the insertion loss decreases. Insertion loss consists of conductor loss and dielectric loss, both of which increase with frequency. Other properties of the material, such as its moisture absorption capability, coefficient of thermal expansion and mechanical strength should also be taken into account. As the permittivity of the substrate is increased, the average resistance at higher frequencies deceases. A higher permittivity lowers the minimum operating frequency because of a decrease in the frequency at which the first resistive peak occurs. The number of oscillations in the resistance and reactance also increases with permittivity. The substrate thickness also has a substantial effect on the performance of the antenna. Thicker substrates can be used to decrease the minimum usable frequency. Schaubert [10] conducted a study of the effect of dielectric substrate thickness and permittivity on the performance of infinite Vivaldi antenna arrays in the thickness and permittivity on the performance of infinite Vivaldi antenna arrays. He found that dielectric loading usually improves the performance of a given antenna design at the lower end of the operating band.

While selecting a substrate material, we also considered its material, fabrication and assembly costs. For example, Roger'ssubstrates are very suitable for use at high frequencies, but the processes used to fabricate Roger's material boards are costly, in addition to the high cost of the material itself. The dielectric constant of FR4 substrate is about 4.4 and the dielectric constant of RTDuroid 5880 substrate is about 2.2. Initially, we fabricated the designed antenna with FR4 substrate and secondly with RtDuroid 5880 substrate, the simulation and measured performance results are compared. Finally, we found that the lower permittivity substrate results better radiation efficiency, gain, beamwidth, and wideband operation.

Design Parameters of aVivaldi Notch-Antenna

The schematic of the three layers forming thecomplete dual layered exponentially tapered slot antenna (Vivaldi notch-antenna) assembly viz., namely; bottom layer, top layer andthe middle layer (stripline feed) is shown in Fig.1. The design parameters of a Vivaldi tapered slot antenna with square cavity tapered slot and radial stub stripline feed aredefined in Fig.2. The parameters of the antenna geometry can be classified into twocategories: substrate parameters (relative dielectric constantε_r, and thickness$t$) and antenna element parameters, which can be subdivided into the stripline /slotline transition, the tapered slot, and the stripline stub and slotline cavity.

The model illustrates two substrates back to back consisting of radiating flare geometries on the two opposite faces. One of the substrate is etched completely on the opposite side of the flare and the other substrate consists of stripline feed being printed and sandwiched between the two substrates containing the flares.The stripline-to-slotline transition provides a wide frequency bandwidth over which the return loss is lesser than -10dB [11]. The flares act as an impedance transformationnetwork between free space and the stripline feed. Radiation fromthe antenna occurs when the slotline impedance is matched to theimpedance of free space.

The stripline/slotline transition is specified W_{ST} (stripline width) and W_{SL} (slotline width). The exponential taper profile is defined by the opening rate R and two points $P_1(z_1,y_1)$ and $P_2\,(z_2,y_2)$

$$y = c_1e^{Rz} + c_2 \qquad (1)$$

where,

$$c_1=\frac{y_2-y_1}{e^{Rz2}-e^{Rz1}},\quad c_2=\frac{y_1\,e^{Rz2}-y_2\,e^{Rz1}}{e^{Rz2}-e^{Rz1}}$$

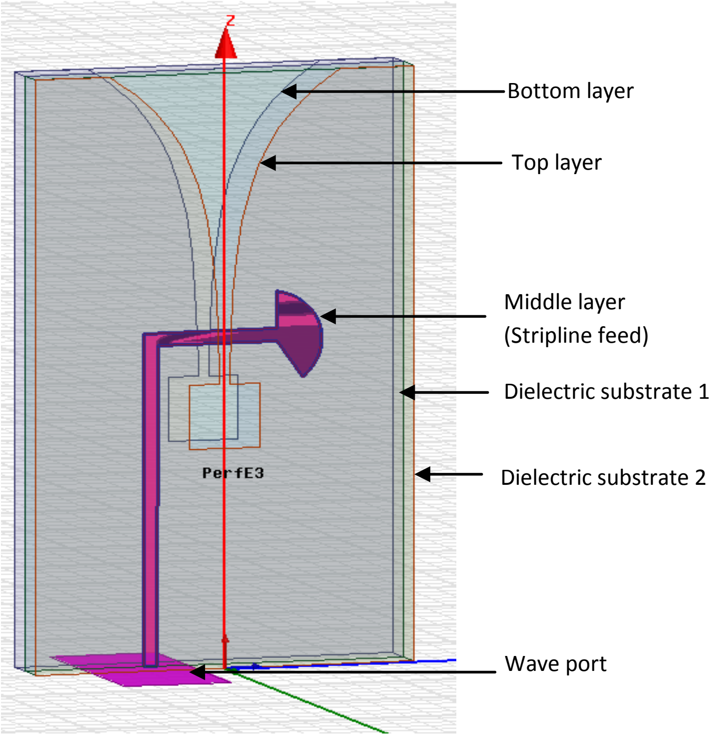


Figure 1: Schematic of Vivaldiantenna geometry

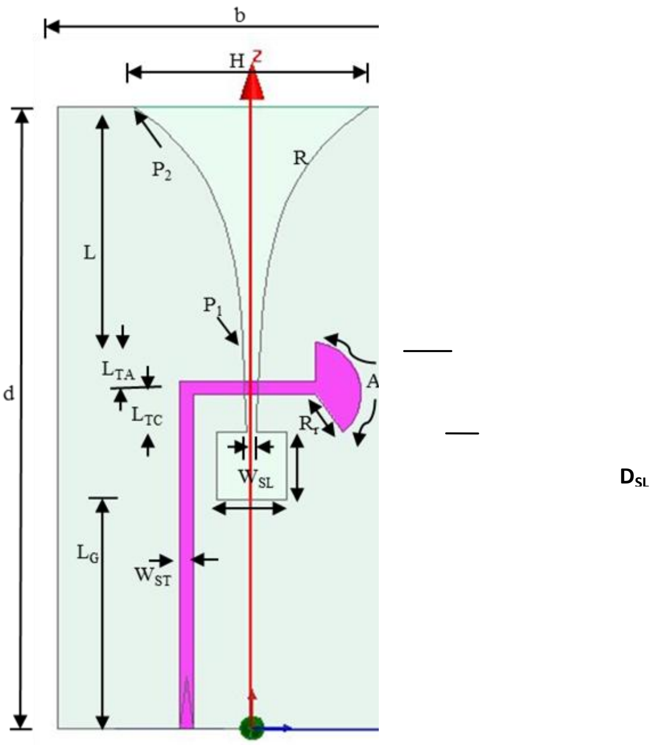
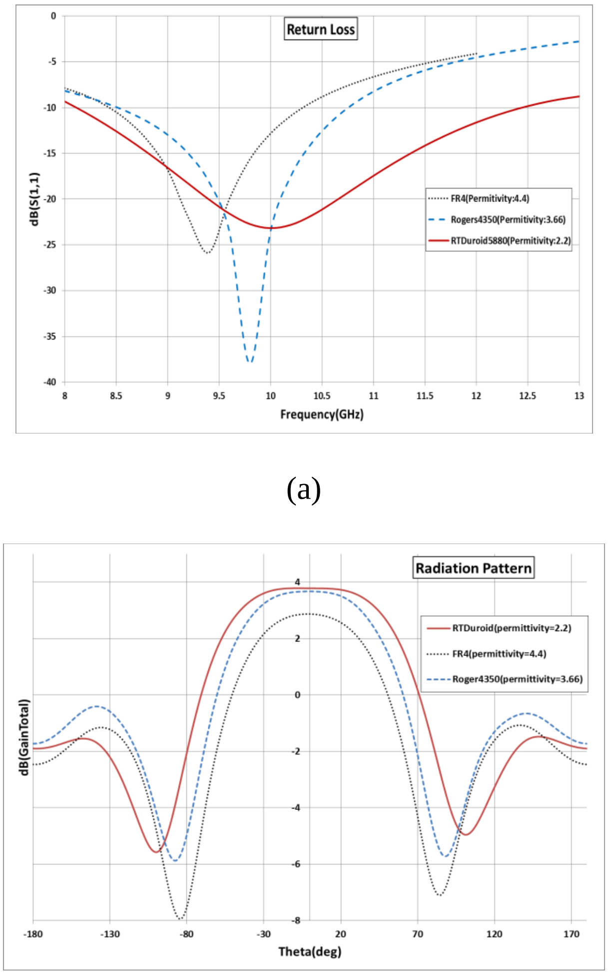


Figure 2: Definition of parameters of Vivaldi TaperedSlot antenna with square cavity exponentiallytapered slot and radial stub stripline feed

The taper length L is z_2-z_1 and the aperture height H is $2(y_2-y_1)+W_{SL}$. In the limiting case where opening rate R approaches zero, the exponential taper results in a so-called linearly tapered slot antenna (LTSA) for which the taper slope is constant and given by $s_o= (y_2-y_1)/(z_2-z_1)$. For the exponential taper defined by (1), the taper slope s changes continuously from s_1 to s_2, where s_1 and s_2 are the taper slope at $z=z_1$ and $z=z_2$, respectively, and $s_1<s<s_2$ for $R>0$. The taper flare angle is defined by $\alpha = \tan^{-1}s$. The flare angles, however, are interrelated with other defined parameters, i.e H, L, R and W_{SL}. Dimensions all in mm: H= 8.5; L=10.6; R=0.36;W_{SL} =0.2. In this study, Distance from the transition to the taper (L_{TA}) and Distance from the transition to the slotline cavity (L_{TC}) are taken as 1mm each. The Radius of radial stripline stub (R_r=2.02 mm) and square slotline cavity (D_{SL} = 2.6 mm x 2.6mm) are investigated in this parametric study. The bandwidth of the antenna was improved with these non-uniform stubs and also noted that radial stub was more advantageous regarding the overlapping between stripline and slotline stubs. The stripline feeding increased the antenna bandwidth compared with the microstrip feeding.

Results, Discussion and Performance

The Vivaldi dual layered exponential tapered slot antenna is designed with three different substrates: 1) higher thickness (ε_r = 4.4) FR4 substrate, 2) with medium thickness (ε_r =3.66) substrate Rogers 4350 and 3) with thin substrate (ε_r = 2.2) RtDuroid5880. The simulated results of return loss S(1,1) parameter and radiation patterns are shown in Figures 3(a) and 3(b). The Table 1 shows the comparison between three different substrate antenna parameters and its performance for selecting a wide band, wide beam, and wide scan antenna material suitable for X-band radar applications. Finally, we found that the lower permittivity material results high gain approximately 4dB, wider beam width greater than 120°andwidebandwidth8-12GHz.



(a)

(b)

Figure3: Simulated (a) S-parameter plotsand (b) Radiation plots of Vivaldi antenna with three different types of substrates and it performance comparison.

Table 1: Comparison between different substrate antennas and its performance for selecting a wide band frequency antenna material

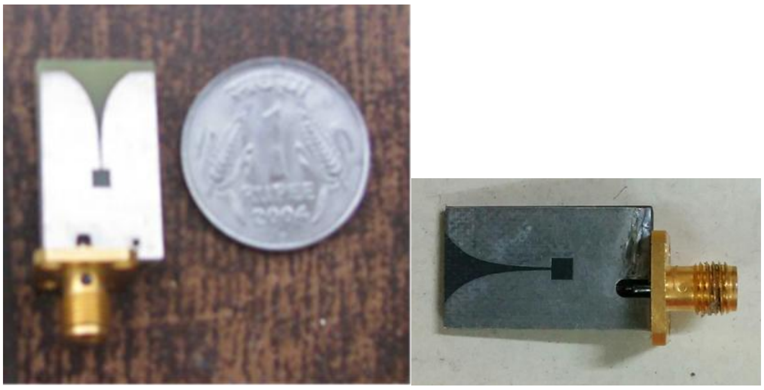
Antenna Parameters	Low Permittivity substrate (ε_r = 2.2)	Medium Permittivity Substrate(ε_r = 3.66)	High PermittivitySubstrate(ε_r = 4.4)
Resonant Frequency(GHz)	10	9.8	9.4
Return Loss (dB)	-23	-38	-26
Gain(dB)	3.9	3.7	2.86
Bandwidth(GHz)	8.1-12.4	8.5 – 10.8	8.4 – 10.3
3dB Beamwidth (degrees)	>120^o	>110^o	>100^o
VSWR	< 1.5	< 2	< 2

Fabrication and Measurements

The Vivaldi Tapered Slot antenna is fabricated with optimized dimensionson FR4 substrate with permittivity ε_r =4.4 with thickness 1.6mm which is shown in Figure 4(a). The Vivaldi antenna is fabricated with the same dimensions with RtDuroid5880 substrate with permittivity ε_r =2.2 with thickness 0.79mm which is shown in Figure 4(b). The antenna is having two substrates such as top and bottom consisting of radiating flare geometries on the two opposite faces. One of the substrate is etched completely on the opposite faces. One of the substrate is etched completely on the opposite side of the flare and the other substrate consists of stripline feed being printed and sandwiched between the two substrates containing the flares. The top, bottom and middle layers are forming the complete antenna. It is fabricated using printed circuit processing techniques. The two substrates were bonded together with the glue them together without any air gaps. The measured results of S_{11} parameter, VSWR and Radiation patterns of two different substrate antennas are shown in Figures 5, 6, 7 and 8. A slight difference is observed between the measurement values and simulated values. The results from simulation and measurement are in good agreement.

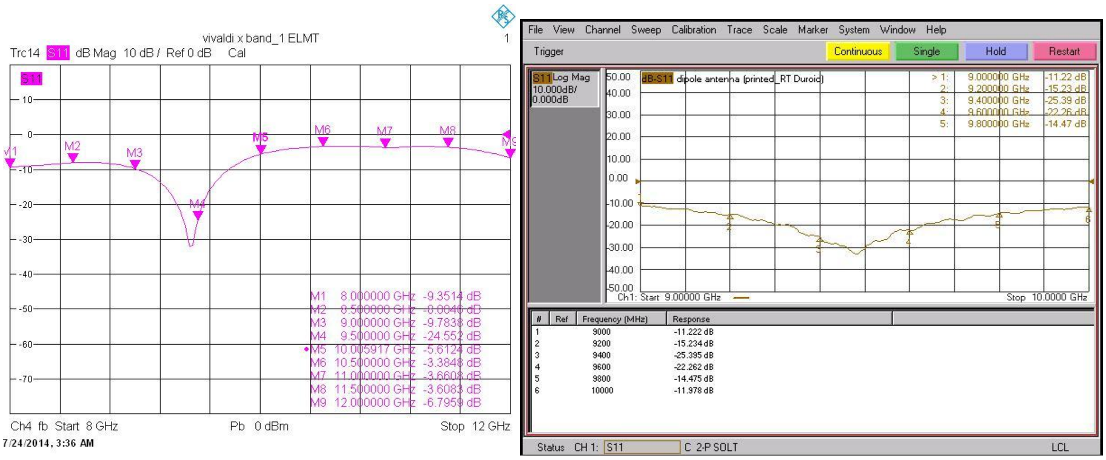
The Vivaldi antenna has been designed to operate only in X-band frequency. The measured return loss of single element with FR4 substrate is achieved less than -10dB for the band of frequency 9GHz to 9.8GHz with the resonating center frequency 9.5GHz shown in Figure 5(a) and the VSWR is less than 2 units for the same frequency band shown in Figure 6(a). The Figure 7(a)shows the simulated radiationplots in E-plane and H-plane, respectively of isolated Vivaldi antenna element illustrating the achieved 3dB Half power beamwidth (HPBW) greater than 120^o in H-plane and 110^o in E-plane with gain of approximately 3-dB for 8.4 to 10.4

GHz operating frequency. The Figure 7(b) illustrating the measured radiation patterns with gain 3dB and beamwidth 82.84°vertically polarized towards Azimuth direction. The measured return loss of single element with RtDuroid5880 substrate is achieved less than -10dB for the band of frequency more than 9GHz - 10GHz with the resonating center frequency 9.5GHz shown in Figure 5(b) and the measured VSWR is less than 1.5 units for the same frequency band shown in Figure 6(b). The Figure 8shows the simulated radiation patterns in E-plane and H-plane, respectively of isolated Vivaldi antenna element illustrating the achieved 3dB Half power beamwidth (HPBW) greater than 137° in H-plane and 120° in E-plane with gain of approximately 4-dB for 8GHz – 12GHz operating frequency.



(a) (b)

Figure4: Fabricated Vivaldi Tapered Slot Antenna with Stripline Feed. (a)High permittivitysubstrate (FR4) (b) low permittivity substrate (RtDuroid5880).

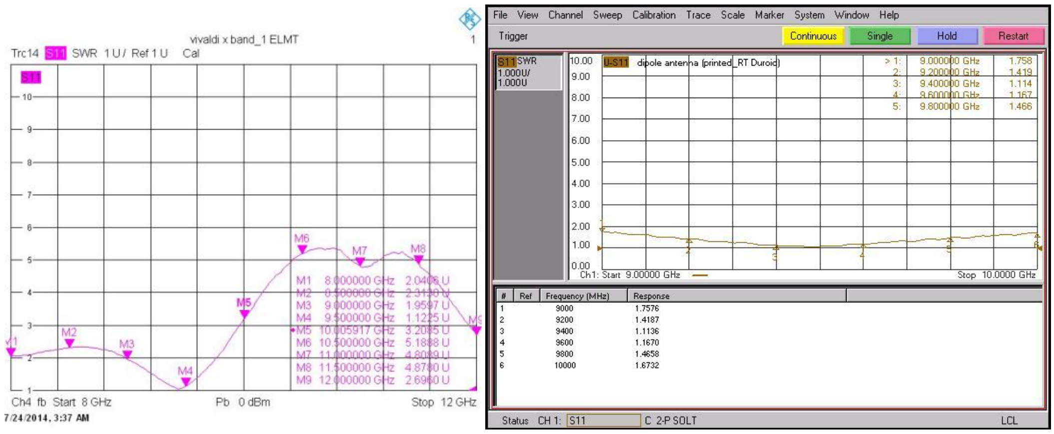


M1	8.000000 GHz	-9.3514 dB
M2	8.500000 GHz	-8.0046 dB
M3	9.000000 GHz	-9.7838 dB
M4	9.500000 GHz	-24.552 dB
• M5	10.005917 GHz	-5.6124 dB
M6	10.500000 GHz	-3.3848 dB
M7	11.000000 GHz	-3.6608 dB
M8	11.500000 GHz	-3.6083 dB
M9	12.000000 GHz	-6.7959 dB

#	Ref	Frequency (MHz)	Response
1		9000	-11.222 dB
2		9200	-15.234 dB
3		9400	-25.395 dB
4		9600	-22.262 dB
5		9800	-14.475 dB
6		10000	-11.978 dB

(a) (b)

Figure5: Measured Return Loss S(1,1) of Vivaldi antenna. (a) High permittivity substrate ($\varepsilon_r = 4.4$) and (b) low permittivitysubstrate ($\varepsilon_r = 2.2$)



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M1    8.000000 GHz   2.0406 U
M2    8.500000 GHz   2.3130 U
M3    9.000000 GHz   1.9597 U
M4    9.500000 GHz   1.1225 U
M5   10.005917 GHz   3.2085 U
M6   10.500000 GHz   5.1888 U
M7   11.000000 GHz   4.8089 U
M8   11.500000 GHz   4.8780 U
M9   12.000000 GHz   2.6960 U
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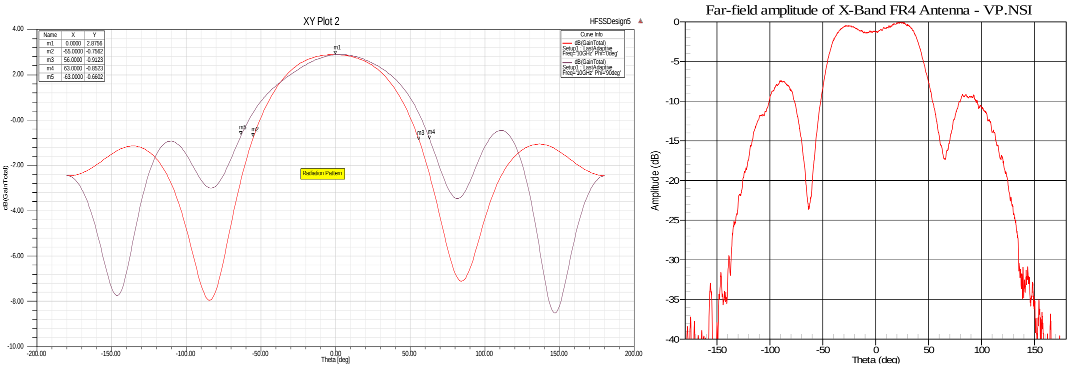
> 1:   9.000000 GHz   1.758
  2:   9.200000 GHz   1.419
  3:   9.400000 GHz   1.114
  4:   9.600000 GHz   1.167
  5:   9.800000 GHz   1.466
```

#	Ref	Frequency (MHz)	Response
1		9000	1.7576
2		9200	1.4187
3		9400	1.1136
4		9600	1.1670
5		9800	1.4658
6		10000	1.6732

(a) (b)

Figure 6: Measured VSWR of Vivaldi antenna. (a) High permittivity substrate (FR4) and(b) low permittivity substrate(RtDuroid5880)



Name	X	Y
m1	0.0000	2.8756
m2	-55.0000	-0.7562
m3	56.0000	-0.9123
m4	63.0000	-0.8523
m5	-63.0000	-0.6602

(a) (b)

Figure 7: Radiation Patterns of FR4 substrate (ε_r = 4.4) Vivaldi antenna. (a)Simulated Radiation patternsin E and H-plane and (b)Measured Radiation Pattern in E-plane

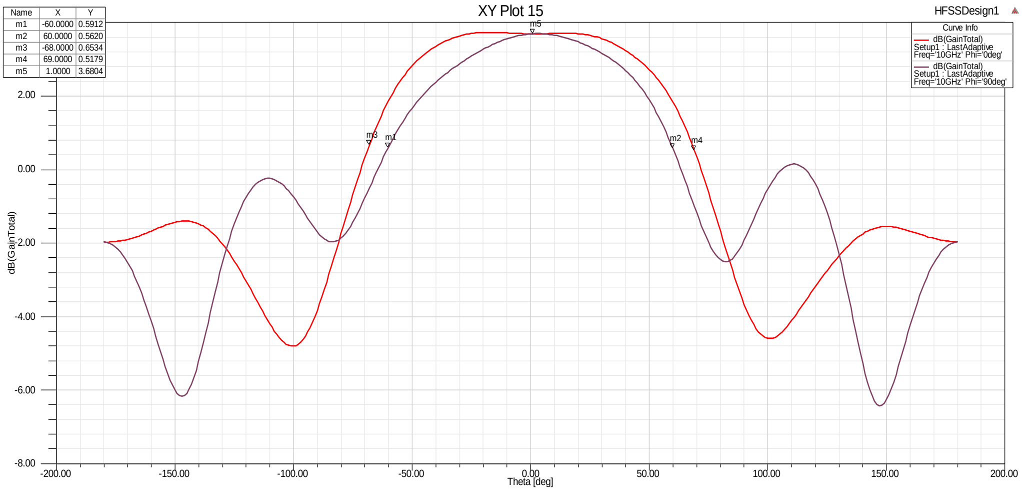


Figure 8: Radiation patterns of RtDuroid substrate ($\varepsilon_r = 2.2$) Vivaldi antenna in E-plane and H-plane

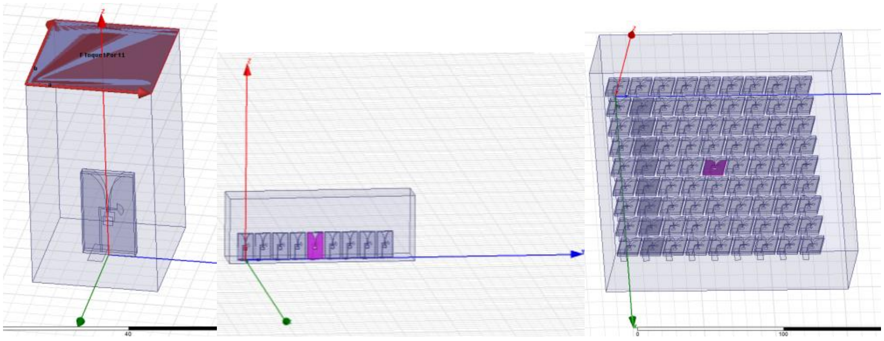
The results are demonstrated that the low permittivity dielectric substrate($\varepsilon_r = 2.2$) Vivalditapered slot antenna has good performancefor X-band airborne radar applications. It has high gain, low sidelobes, wide bandwidth, wide beamwidth and widescan angle. Thus, for the design of array with RtDuroid substrate had been taken. The results are demonstrated that the Vivaldi exponential tapered slot antenna has good performance for widescan phased array covering X -band.

Design of Vivaldi Antenna Array and Results

Array performance strongly depends on the mutual coupling in a wide bandwidth and wide scanning arrays. The measurement of mutual coupling makes it easier to predict the scan performance of the array. The antenna design parameters are optimized based on unit cell approach where infinite array is emulated by enclosing the antenna element by electric/magnetic walls which act like mirror walls showing infinite elements on either side of the grid along x- or y-directions [12]. The Figure 9(a) shows the HFSS model of unitcell of antenna element with rectangular lattice arrangements with Floquet modes. The linear array is designed with 9-elements, displaced a distance, d, all the elements are excited uniformly. All the coupling effects are accounted for in the scan element pattern. The Figure 9(b) shows the HFSS model of one-dimensional antenna array with 9-elements arranged in a linear grid with spacing, dy = 16mm as per the desired specifications. The inter-element spacing is defined by the Equation (2).A planar array of 9x9 elements arrangement having inter-element spacing's; dx = 0.518λ and dy = 0.536λ, in H-plane and E-planes has been chosen in this array design shown in Figure 9(c).

$$dy = \frac{\lambda}{1+Sin\theta} \tag{2}$$

The return loss of the Centre element in the array environment is shown in Figure 10 which is also less than -10dB for the frequency band 8GHz to 12GHz including mutual coupling effects. The VSWR is less than 2-units for X-band frequency shown in Figure 11. The simulated radiation patterns shown in Figure 12with narrow 3dB beam width of 10^{o} in Elevation cut and more than 120^{o} beam width in Azimuth cut. The simulated polar plots of an array are illustrated in Figures 13 (a) and (b) shows the fan shaped beam pattern in H-plane(ϕ = 0^{o}) and narrow beam pattern in E-plane (ϕ = 90^{o}) respectively at 10GHz with the Gain of 13dB. The side lobe level approximately -13dB down from the main lobe. Thus the designed Vivaldi antenna has been optimized in the array environment. These studies have clearly established the suitability of the designed array element, as a candidate for wide scanning active phased array radar operating in X-band operating frequency.



(a) (b)(c)

Figure 9: Vivaldi antenna array design in HFSS. (a)Unit cell model, (b) Linear array and (c) Planar array.

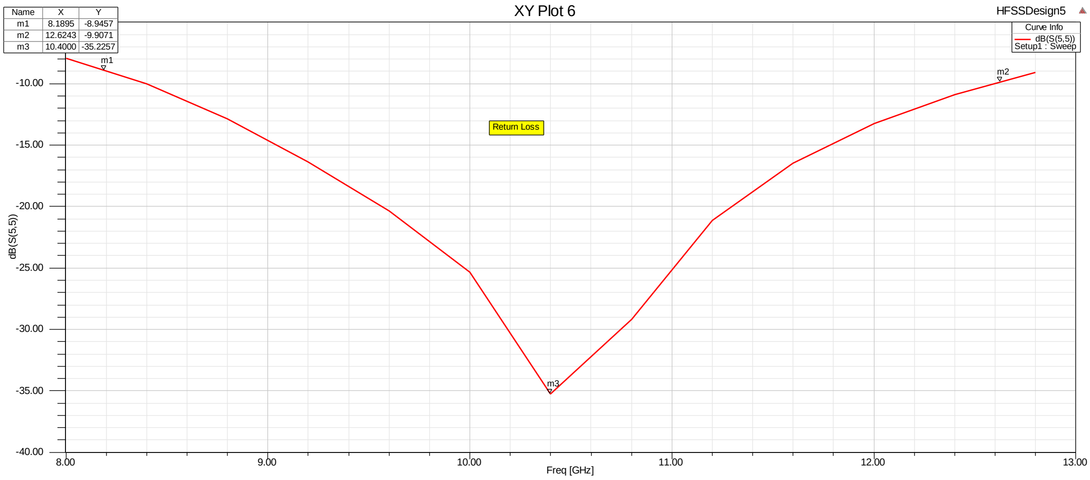


Figure 10: Active Reflection coefficient dBS(5,5) of linear array

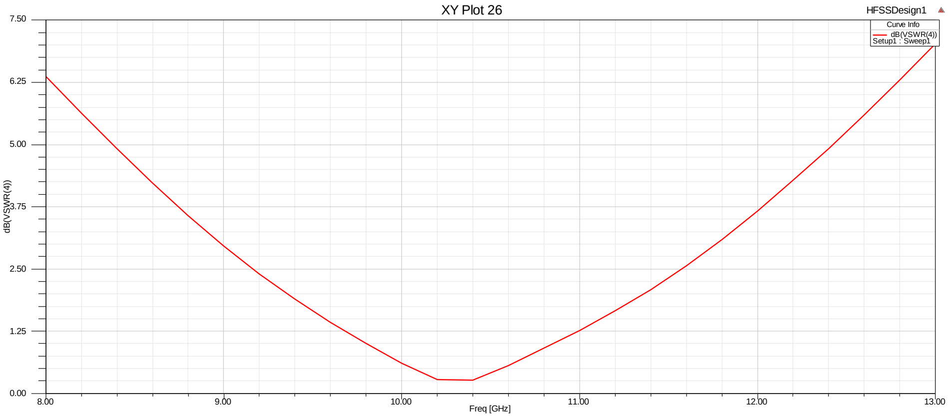


Figure 11: Voltage standing Wave Ratio plot.

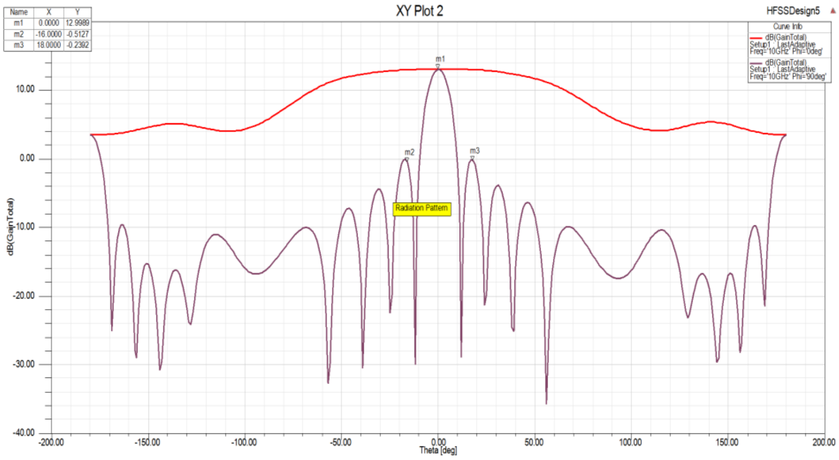
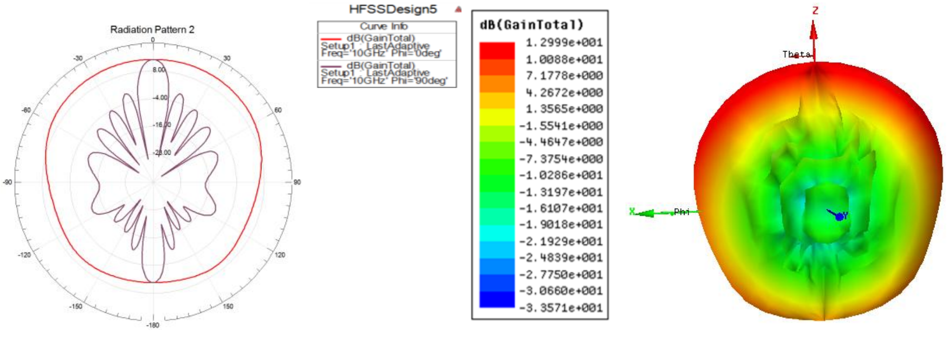


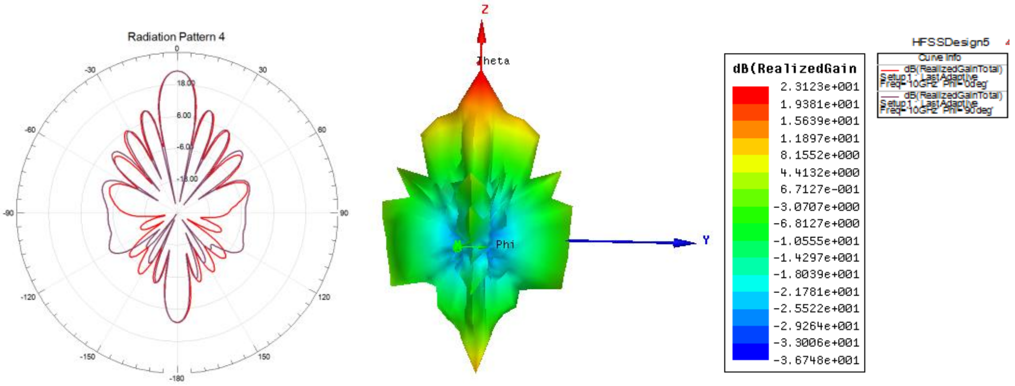
Figure 12: Simulated Radiation Patterns of Linear Array with 9-Elements in E-Plane and H-Plane.



(a) (b)

Figure 13: Simulated Radiation Patterns of Linear Array with 9-Elements (a) Polar Plot and (b) 3-D Fan Shaped Pattern in E-Planewith the Gain of 13dB.

The Figure 14and 15 shows the radiation patterns of planar array (9x9=81elements) with the Gain of 23 dB and the sidelobe level is -13dB down from main lobe in E-plane and H-plane with the 3-dB beamwidth of 10degrees in both E-plane and H-plane. The scanned beam patterns of uniformly illuminated 81 elements antenna array including the element pattern showing the ability of array to scan over the desired scan volume mentioned previously in H and E-planes respectively. It has been shown in these figures that the planar array can scan over the desired scan volume of ±60^{o} in E-plane and ±55^{o} in H-plane.Thus, the performance of designed element has been proved in planar array environment, as a prime candidate for active phased array antenna with X-band operating frequency.



(a) (b)

Figure 14: Simulated Beam Patterns of Planar Array (a) Polar Plot (b) 3-D Pencil Beam Pattern.

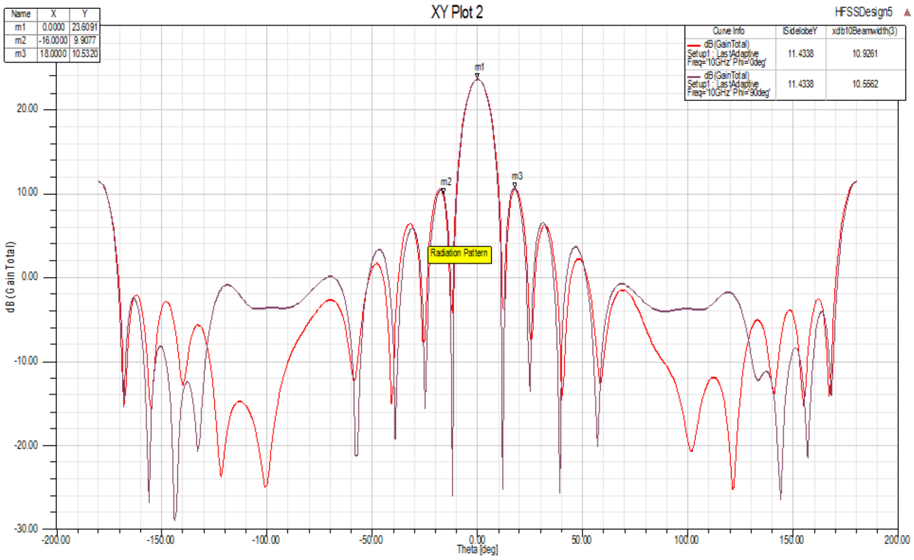


Figure 15: Rectangular Plot of Planar Array Antenna with Gain of 23.6 dB and Sidelobe Level -13 dB Down.

Conclusion

A wide band Vivaldi antenna has been fabricated with two different permittivity substrates for wideband applications. The antenna performance results shown that low permittivity substrate have high gain, wide bandwidth, wide beamwidth, wide scan angle and lesser VSWR. This antenna element satisfied the requirements of maximum reflection coefficient -10dB and VSWR less than 2units. Realized antenna has shown symmetric patterns with high gain of 4dBoperating in X-band frequency. The wide beam width of $120^o$and widescan angle performance has been achieved and the antenna is optimized in array environment. Thus, the designed tapered slot antenna is promising candidate forthe airborne active phased array radars and other similar applications.

Acknowledgement

The authors will like to acknowledge the support extended by DRDO in carrying out the work. They would like to thank the antenna measurement and fabrication divisions at LRDE for their support in realizing the antenna structure.

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