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Design of Compact Vivaldi Antenna Arrays for AESA Radar System

Babu Saraswathi K. Lekshmi
Department of Electrical and Electronics Engineering,
Noorul Islam University, India

I. Jacob Raglend
Department of Electrical and Electronics Engineering,
Noorul Islam University, India

ABSTRACT

This paper demonstrates a low-profile, wide band, miniaturized, Stripline fed double layered exponentially tapered slot antenna with a wide-scan capability and 10% bandwidth at the X-band frequency has been designed, fabricated, and tested. The antenna is optimized with a total size equal to 14.2x24.1x1.4 mm^3 and is capable of achieving the desired bandwidth experimentally. The 9-element array and feeding network based on 1:9 T-junction power divider was employed to compose the linear array. The array elements are operating with return loss lower than 10 dB at X-band frequency. Measured results of single elements in isolated and array environment are achieved, both have a wide 3-dB beam width better than 107^o in the E- and H- planes, which is capable of a linear array with wide scan angle ±55^o. The linear array has a half power beamwidth of 11 degrees with side-lobe level of -12dB at 10GHz with a gain of 12dBi. These features make the antenna array fit for X-band airborne radar applications.

Keywords: Dual layered Exponentially tapered slot antenna, slotline, X-band, wide beam, Radar, Return loss, AESA antenna, Stripline.

INTRODUCTION

Lewis *et al*. introduced tapered slot antenna (TSA) in 1974 [1]. It is a key candidate for wide-scan arrays operating at a wide band frequency. Vivaldi antenna is a category of TSA used in an Ultra wide band (UWB) technology. It was first designed by Gibson [2] in 1979, has an exponentially tapered slot line. Vivaldi arrays are small in size, simple and weightless, easy to fabricate, enable compact arrays and they are highly efficient for wideband phased array antennas [3-5].

Phased arrays are essential to function over wide scan angle and wide bandwidths to offer multiple operations, which is proficient of simultaneous and time interleaving, electronic warfare and communication functions [6-10]. In response to that need, a design of TSA for airborne radar applications has been offered in this paper. The TSA with Strip line feed network, which is capable of operating in 8GHz to 12GHz frequency and scan angle above ±60^o in H- and E-planes. The present work concentrates on the design of the slot taper to increase power transformation and decrease reflection. The exponential tapers have been designed using a close form equation [8]. The three parameters decide the performance of the exponential tapered slot antenna, viz. i) Opening of the slot which decides the operating frequency, ii) smoothness of the exponentially TSA, which reduces the phase error across the frequency and iii) balun limits the antenna bandwidth. The whole design of the antenna has been repeated using an electromagnetic simulator, High Frequency Structure Simulator (HFSS) [11].

Several studies about the phased array antenna for wide-scan and wideband applications have been recently proposed [12-15]. The Bengt *et al.* [12] developed a slotted waveguideantenna with achieving scan area less than ±40° in X-band. Chen and Wang [13] designed an array and feeding network, but the measured outcomes were not revealed in their work to confirm the performance of the array. When designing an array antenna, complications related to the incorporation of antenna element and feeding network such as the mutual coupling effect between elements need to be enunciated.

In this paper, a nine-element linear X-band antenna array has been designed and the radiation characteristics of the array are studied numerically and tested experimentally. A number of intermediate steps were done, to reach the design of the X-band array and summarized in this paper as given below. In Section 2, the design of exponential tapered slot antenna has been explained. This antenna element is used to constitute the X-band antenna array. The design of the array with uniform distribution is presented to analyze the element in an array environment, which is described in Section 3. In Section 4, the design of T-junction power divider which is used for feeding the 9-element linear array has been explained. Measured results are offered in Section 4 and the conclusions are condensed in Section 5.

TAPERED SLOT ANTENNA DESIGN

Parametric Study

Tapered Slot Antenna or Vivaldi antenna is fed with Strip line-feed which comprises of a Strip line-to-slot line transition, a Strip line stub, a slot line cavity and a tapered slot. The design parameters of a tapered slot antenna with square cavity and radial stub strip line feed are given in Figure 1. The Specifications of each parameters of Tapered slot antenna are given in Table 1.

Table 1: Design Specifications of double layered TSA

Parameters	Specifications (in mm)
Strip line width (W_{ST})	0.5
Angle of radial strip line stub (A_R)	130^o
Antenna width (b)	14.2
Antenna length (d)	24.1
Length of slot line cavity from ground plane (L_G)	8.9
Aperture height (H)	8.5
Taper Length (L)	10.6
Opening Rate (R)	0.36
Slot width (W_{SL})	0.2
square slot line cavity (D_{SL})	2.6x2.6
Radius of radial strip line stub (R_r)	2.02

Distance from the transition to the taper (L_{TA})	1
Distance from the transition to the slot line cavity (L_{TC})	1

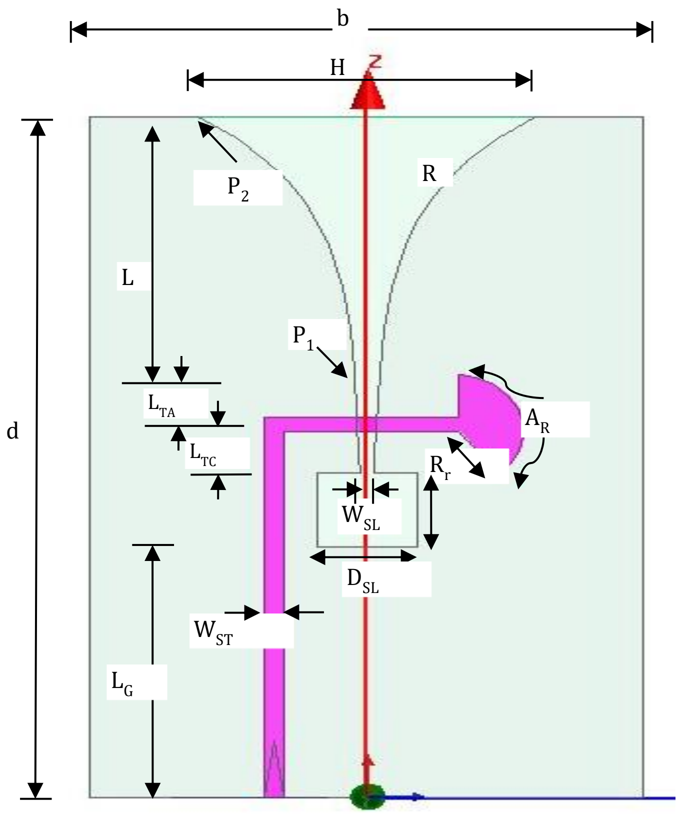


Figure 1: Definition of parameters of Tapered slot antenna.

The RTDuroid 5880 dielectric substrate is used for this design with relative permittivity $\varepsilon_r = 2.2$ and thickness t = 0.7 mm. The strip line/slot line transition is indicated by W_{ST} (strip line width) and W_{SL} (slot line width). The exponential taper shape is defined by the opening rate R and two end points P_1 (z_1, y_1) and P_2 (z_2, y_2)

$$y = c_1 e^{Rz} + c_2 \quad \text{-------------------} \qquad (1)\ [3]$$

Where,

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

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

The length of exponential taper (L) is z_2-z_1 and the height of aperture (H) is $2(y_2-y_1)+W_{SL}$. For linearly tapered slot antenna (LTSA), the opening rate R is zero and taper slope is constant, which is given by $s_o= (y_2-y_1)/(z_2-z_1)$.

The exponential taper is calculated by equation (1), the taper slope s varies from s_1 to s_2, where s_1 and s_2 are the taper slope at $z=z_1$ and $z=z_2$ and $s_1<s<s_2$ for $R>0$. The taper flare angle is designed by $\alpha = \tan^{-1}s$. The flare angles are correlated with the other parameters, i.e H, L, R and W_{SL}. The antenna bandwidth is enhanced with non-uniform stub like radial stub. Further, radial stub is more advantageous concerning the intersection between strip line and slot line stubs. The strip line feeding increases the bandwidth of antenna compared with micro strip feeding. In this work, non-uniform (radial) stub for stripline and square stub for slot line has been taken for stripline-to-slotline transition.

The geometry of the Dual layered TSA and the various parts assembled in the design are shown in Figures 2 and 3. The assembly represents two substrates, associated back to back, comprising of radiating flare geometries on the two reverse faces. One of the substrates is etched out totally and on the reverse side of the substrate is imprinted with antenna flare. The other substrate consists of radiating flare on one side and the reverse side with strip line feed being imprinted and sandwiched between the two substrates comprising the flares.

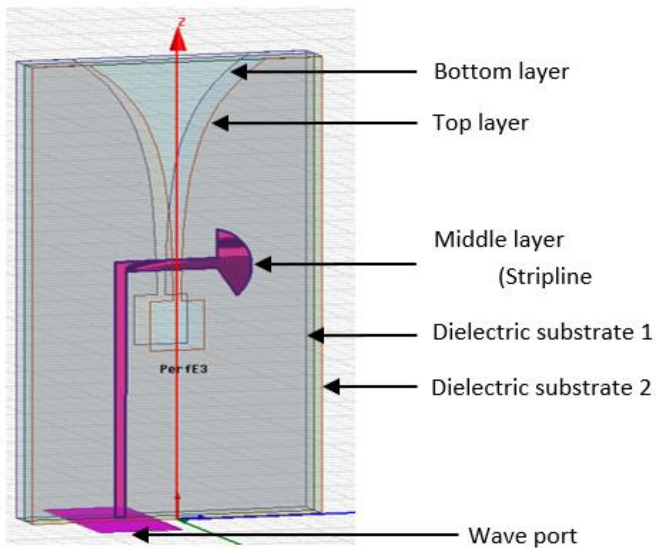


Figure 2: Schematic of double layered Vivaldi Tapered slot antenna geometry.

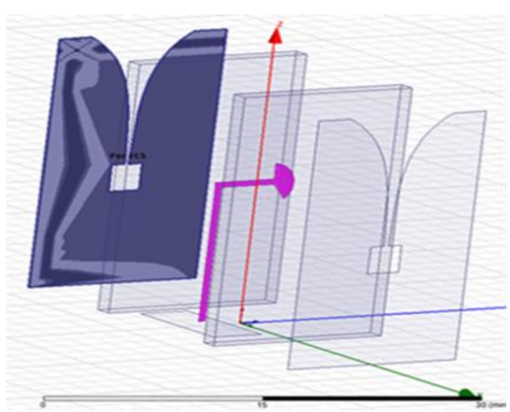


Figure 3: Exploded view of double layered Vivaldi antenna assembly.

Simulations

The simulation results are obtained using ANSYS Electromagnetic simulator HFSS. The S-parameter versus frequency plot in Figure 4 illustrates dB(S(1,1)) which is lower than -10dB for an isolated single element over the frequency of 8 GHz to 12 GHz. The simulation results of radiation patterns of an isolated Vivaldi antenna element illustrate the attained half power beam width (HPBW) better than 120º in the two major planes and gain around 3.6 dBi as revealed in Figure 5. It can be determined from Figure 5, the scan angle is ±68º and 3-dB beam width is 136º for the Azimuth cut (Φ =0º). Further, in the Elevation cut (Φ = 90º), the scan angle is ±60º and 3-dB beam width is 120º. It is perceived that low cross polarization has been achieved for an isolated single element as shown in Figure 6.

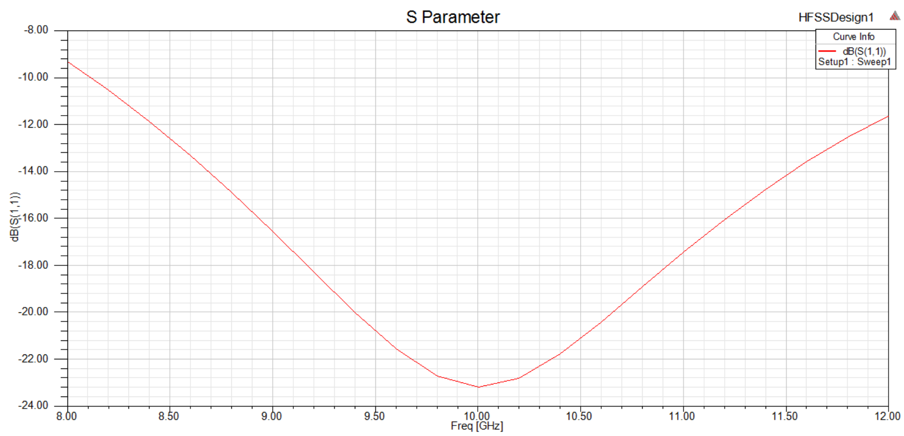


Figure 4: Simulated S-parameter results of double layered Vivaldi antenna.

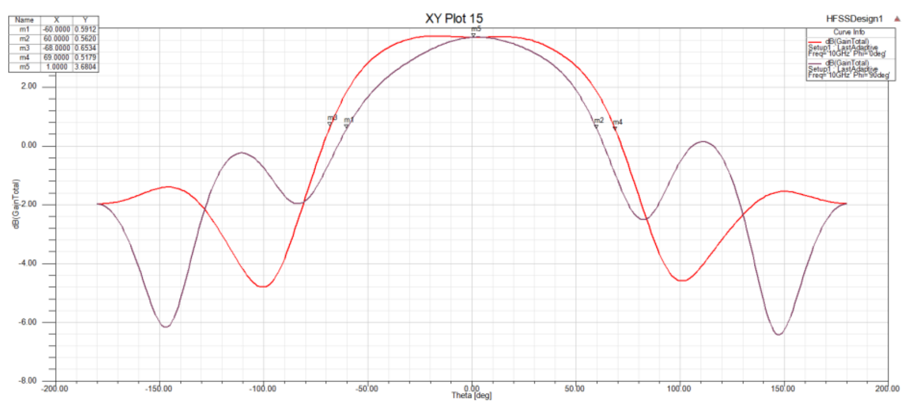


Figure 5: Simulated radiation patterns of double layered Vivaldi antenna at 10GHz in E- and H-planes.

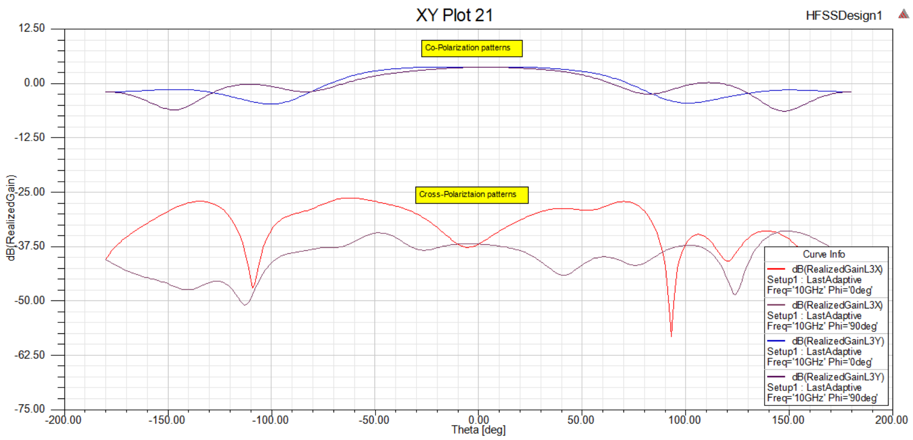


Figure 6: The simulated Co-polarization and Cross-polarization patterns of isolated single element

Fabrication

The double layered Vivaldi antenna is fabricated with designed dimensions described in Table 1. Vivaldi antenna structure has three layers and is fabricated using printed circuit board technology. The antenna is constructed on two 31 mils (0.7mm) Rogers RTDuroid 5880 board. The Cuclad dielectric substrate RTDuroid 5880 with the permittivity ε_r = 2.2. Each board has the designed tapered slot printed on one side of the board. Metallic layer on the other side of one of the boards is removed completely; whereas the other board has the designed Stripline feed on the other side. The two boards are bonded together forming a triplet structure with tapered slot sections on the top and bottom layers and stripline feed on the middle layer. Thus, a stripline fed three-layer structure is obtained.

A 50Ω SMA connector is used to feed the stripline. The center pin of the connector is soldered to the stripline before bonding the two boards. The bonding is realized using Araldite adhesive substance at a temperature above 100^{o}C. The two substrates are bonded together without any air gaps. The final step of the antenna fabrication is to solder the outer pins of the connector to the slotline ground planes in order to realize ground connection of the feeding. The picture of the fabricated Vivaldi antenna is presented in Figure 7.

The isolated single element is simulated with the stripline configuration which is TEM mode, but the fabricated model is hard to connect the connector because of stripline geometry. So the transition has been made from stripline to microstrip line configuration to connect RF Connector. A V-shaped cut has been introduced above the stripline to connect the SMA connector. As we know that microstrip is the Quasi TEM mode, optimization has been made to match with 50Ω connector and the strip line. The final simulated model with v-cut is shown in Figure 1.

Measurements

The S-Parameter of fabricated antenna is measured using a Vector Network Analyzer. The measured results of dBS (1,1) parameter is shown in Figure 8. The measured S-parameter of isolated single element is lower than -10dB over the X-band frequency from 8.9 GHz to 12 GHz with the resonating center frequency of 9.5GHz. This measured result of S-parameter is in good promise with simulated results revealed in Figure 4. As a result of some engineering tolerances while bonding the two substrates together, leads to the little variation in the simulated and actual total thickness of the substrate.

The radiation patterns of double layered Vivaldi antenna are observed in Anechoic Chamber. The measured Radiation patterns are presented in Figures 9(a) and (b) in H- and E-planes, respectively, This patterns of single element demonstrating the attained 3dB beam width better than 101.32^o in the H- and E-planes with a gain of around 4 dBi at X-band operating frequency.

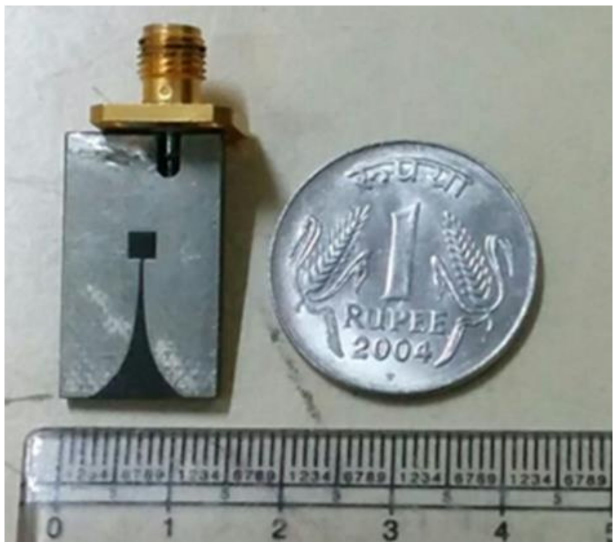
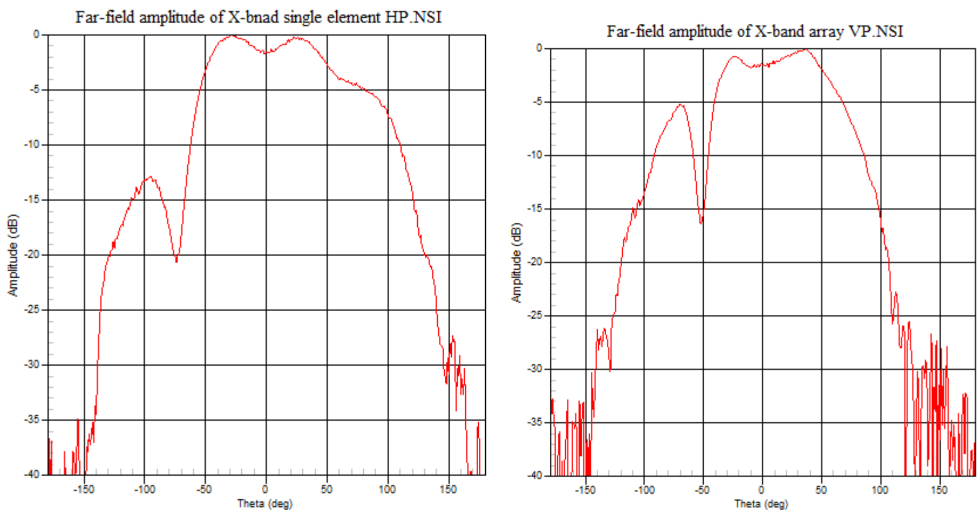


Figure 7: Fabricated double layered Vivaldi antenna

Figure 8: Measured S-parameter of an isolated TSA



(a) H-plane **(b) E-plane**

Figure 9: Measured Radiation patterns of double layered TSA at 10GHz

TAPERED SLOT ANTENNA ARRAY DESIGN

The performance of the Array is toughly depending on the mutual coupling between elements, both in the wide bandwidth and the wide scanning arrays. The linear array is fabricated with 9-elements, with inter-element spacing, dy. All the coupling effects are taken into account in the scan element pattern. The Scan element pattern (SEP) is obtained by exciting only one of the elements, the other elements are ended with matching loads [16]. The Figure 10 shows the fabricated one-dimensional Vivaldi antenna array. To derive a desired specification, an array of 9-elements have been organized in a linear network with a inter-element spacing, dy = 16mm. The separation between elements is determined by the Equation (2).

$$dy = \frac{\lambda}{1+Sin\theta} \quad \text{------------------------} \quad (2)\ [17]$$

The spacing between elements is controlled by the smallest operational wavelength (highest frequency) and wide scan angle. The active reflection coefficient ($\Gamma_m(\theta)$) is the major performance parameter of a wideband array. This is the fraction of power reverted back from the radiating element, while all the elements in the array are illuminated. The active reflection coefficient can be determined by the following equation

$$\Gamma_m(\theta) = \sum_{n=1}^{N} S_{mn} e^{-ikndsin\theta} \quad \text{-------------------} \quad (3)\ [17]$$

When $k = (2\pi/\lambda)$, m is the m^{th} element and S_{mn} is the S parameter between the m^{th} element and n^{th} element. In equation (3), the coupling between the elements S_{mn} are accounted. The center element is excited in array environment and the other elements are connected with 50Ω matched loads.

Measurements

The antenna elements are fed by SMA type RF connectors. For the active reflection coefficient measurement of the center element in the linear array environment, except the center element, ie., 5th element, the other elements are connected with the matched loads (see Figure 10). The S-parameter and the principal plane radiation patterns are measured. The element performance in embedded environment has been analyzed. The measured active S-parameter of the center element (5th element) is lower than -10dB over the desired frequency band, shown in Figure 11. The measured mutual coupling is -16 dB for the close neighboring element to the center element. The measured radiation patterns in H- and E-planes of the center element in the linear array environment is shown in Figures 12 (a & b). It is observed that HPBW in H-plane is 104^{o} and E-plane is 107^{o}. A little reduction in HPBW and increase in cross-polarization have been observed because of the mutual coupling from nearby elements and the presence of a metallic ground plane on which the Vivaldi array has been mounted for radiation patterns measurement.

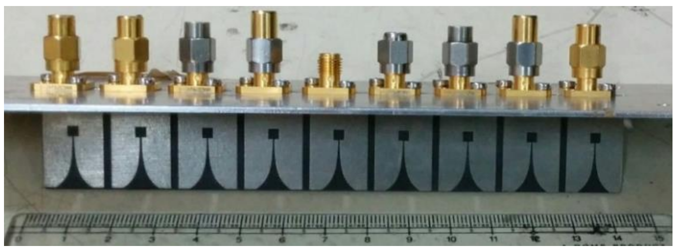
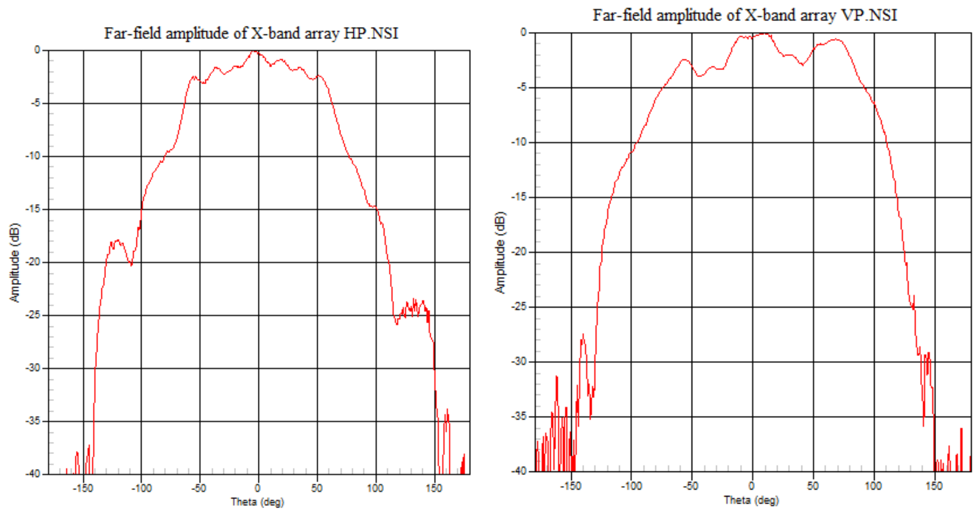


Figure 10: Fabricated double layered Vivaldi array antenna

Figure 11: Measured S-parameter of center element TSA in linear array



(a) H-plane **(b) E-plane**

Figure 12: Measured Radiation patterns of a center element in an array environment at 9 GHz.

Performance Comparisons

The designed Vivaldi antenna is simulated in an infinite array environment with a unit cell approach to optimize the antenna element with rectangular lattice arrangements [12]. The Table 2 shows performance comparisons between simulated results of a single antenna element, measured results of isolated single element and measured results f center element excited in an array environment. It is observed that the measured results of double layered single element in an isolated and in an array environment are in good agreement with the simulation results.

The gain is observed around 4dBi, low cross polarization and maximum beam width around 107^{o} over the desired X-band frequency. The ripples in radiation patterns can be minimized by covering the ground plane with some absorbing materials. These studies demonstrate the aptness of the designed Vivaldi antenna as a better choice for active phased array operating at X-band for airborne radar applications.

Table 2: Performance Comparisons of Vivaldi Antenna

Antenna Parameters	**Simulated results of Vivaldi antenna in Isolated environment**	**Measured results of Vivaldi antenna in Isolated environment**	**Measured results of a center element in Array environment**
Resonant Frequency (GHz)	10	9.5	9.8
dB (S (1,1)) at center frequency (dB)	-23	-30	-26
Gain(dBi)	4	4	4
Bandwidth (GHz)	8 - 12	8.9 - 12	8.9 - 12
HPBW at H-plane	130^{o}	101^{o}	104^{o}
HPBW at E-plane	120^{o}	101^{o}	107^{o}

T-JUNCTION POWER DIVIDER DESIGN

A wideband T-junction power divider has been designed to feed the TSA array shown in Figure 13. The T-junction power divider has 4-section, which delivers power output signals at the output ports, which has well-balanced amplitudes and phases. It is composed with 9-way feed network for powering the 9-elements Tapered slot antenna array.

The 4-stage T-junction corporate power divider makes use of an unequal split T-junction power divider in the 1st stage. The 2nd and 3rd stages are combined of unequal T-junction power splitters to obtain the necessary power distribution. The Spacing between Junctions is equally spaced at 0.54λ. The fabricated 1:9 T-junction power divider for the TSA with uniform distribution operating at 9-10 GHz frequency has been revealed in Figure 14. The input and the nine output ports are harmonized with 50Ω characteristic impedance, so that the power divider can be straight coupled with the tapered slot antennas. The nine phase matched RF cables are used to connect the Vivaldi antenna elements to the output ports of 1:9 way power divider circuit.

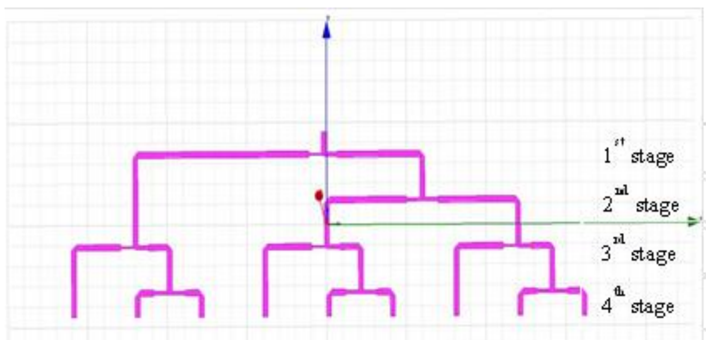


Figure 13: Design of uniformly distributed 1:9 way equal T-junction power divider.

Fabrication

The Figure 14 shows the fabricated double layered Vivaldi array antenna geometry. This structure consists of 9 equal radiating elements and connected to a feeding network. This power divider is built by using microstrip transmission lines on FR4 substrate board with dielectric constant ε_r = 4.4 and substrate thickness of 1.6 mm.

Measurements

The return loss has been measured using VNA and the measurement setup is presented in Figure 15. The radiation patterns are measured in the anechoic chamber shown in Figure 16. The S-parameter results are obtained less than -10dB over the desired X-band frequency as given in Figure 17. The radiation patterns with 3-dB beam width of 12° and the side lobe level lower than -12dB are measured at 9GHz and at 10GHz operating frequency are shown in Figures 18(a and b). Thus, these studies proving that the designed antenna array is suitable for Active electronically scanned array antenna operating at X-band frequency. Further, this antenna array is a prime component for airborne radar applications which can be used in combat aircraft.

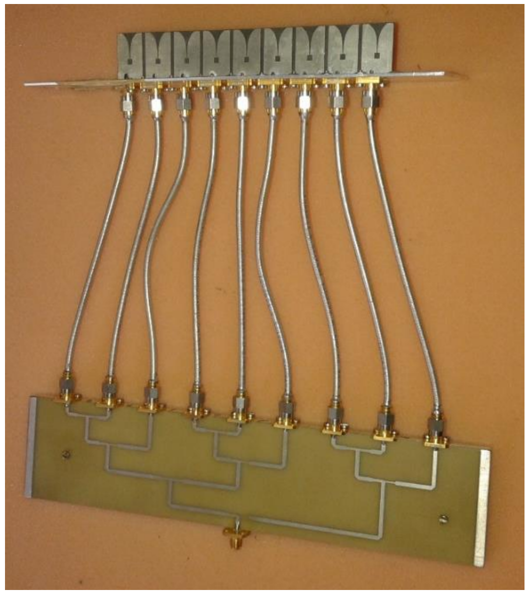


Figure 14: Fabricated double layered Vivaldi array antenna.

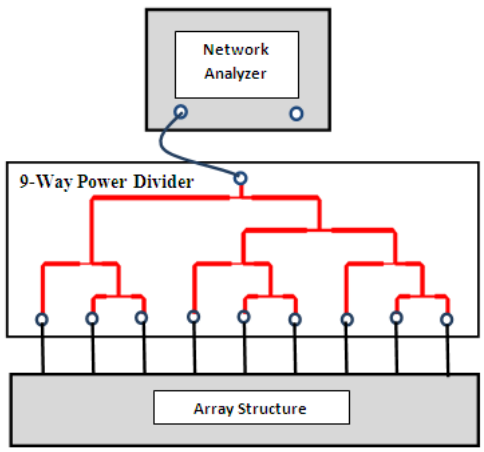


Figure 15: Array Return loss measurement setup.

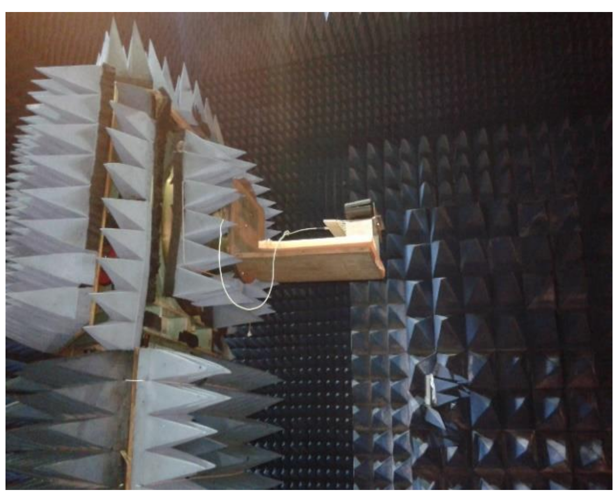
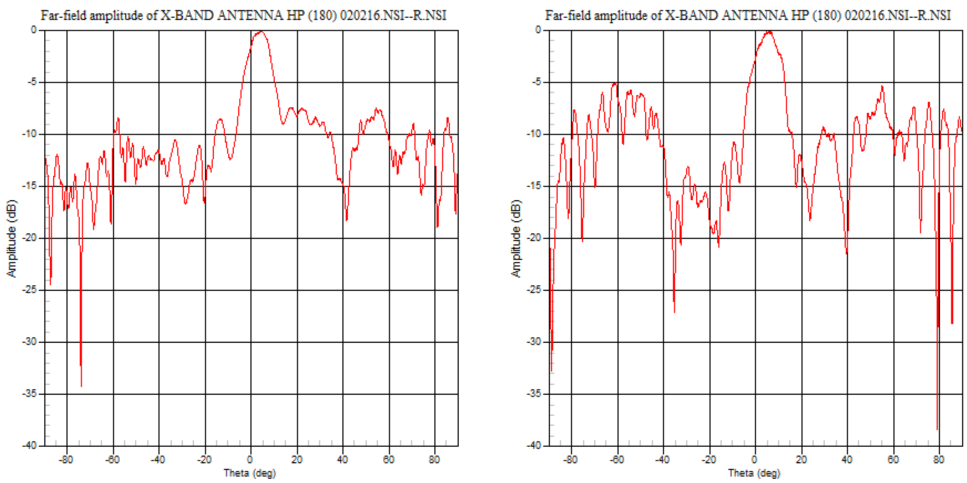


Figure 16: Array radiation pattern measurement setup.

Figure 17: Measured S-parameter results of 9-elements double layered Vivaldi array antenna.



(a) at 9 GHz **(b) at 10 GHz**

Figure 18: Measured Radiation patterns of 9-elements double layered Vivaldi array antenna in H-plane.

Beamforming and Beamsteering of Linear Array

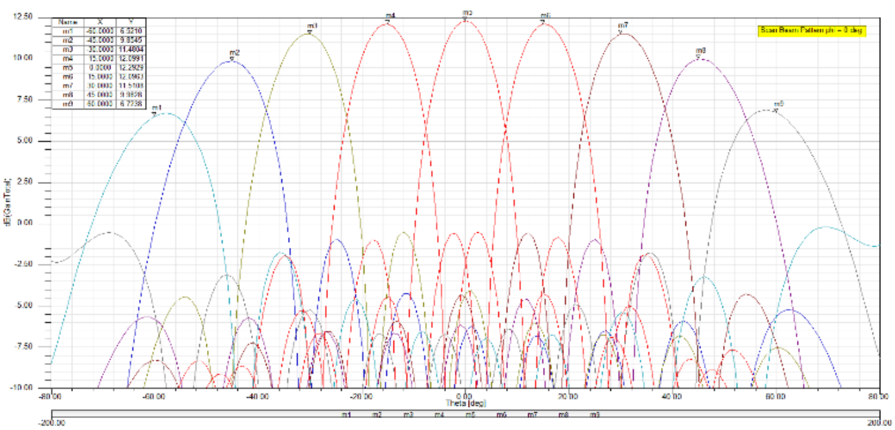
Beamsteering technique is one of the ways to track the target is by using steerable beams. In this case, the adaptive array system is altered to the RF atmosphere when it changes, by dynamically altering the radiation pattern to enhance the system response. The changes in the beam pattern are based on preferred signal and interference locations. When signals induced at each element of the array are collected, only one output of the array is formed. In conventional beamforming, only the phase of the signals from different elements is adjusted to point the beam in the preferred direction. The gain of each element keeps same, which controls the total gain of the array on the beam pointing direction. Further, there is no change in the shape of the antenna pattern, that is, the sidelobes pertaining to the main beam will not change when it is pointed in various directions by changing different phases. To find the phases for different beam steering angles at different input element port (N), the following equations (4) and (5) can be used [18]. The phase (ψ) at Beam steering angle (θ_o)

$$\psi = NkdSin\theta_o \text{ -------------------------------} \quad (4)[18]$$

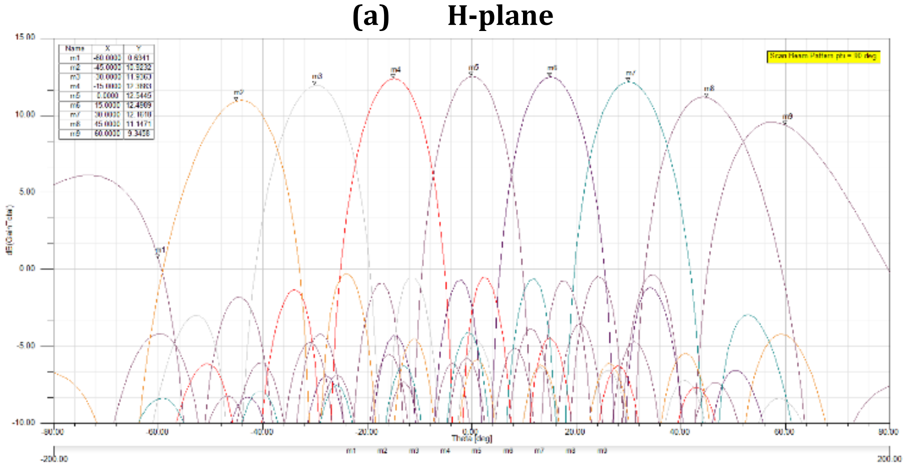
The Figure 19(a & b) shows the simulated results of scanned beam patterns at 10GHz at different beam steering angle (≈NkdSinθ) ±15°, ±30°, ±45° and ±60° of uniformly illuminated 9-elements antenna array including the element pattern showing the ability of the array can scan over the desired scan volume around 120°. The Table 3 represents the input specifications and output characteristics of the uniformly distributed array. These studies show the ability of designed widebeam double layered Vivaldi antenna is the suitable element for wide angle scanning phased array antenna operating at X-band frequency.

Table 3: Input and Output characteristics of uniform linear array

Input Specifications	
Configuration	Linear array
Type of array	Uniform
No. of Elements	N = 9
Element Spacing	0.535λ
Output Specifications	
AF Directivity	12.5 dB
AF HPBW	11°
AF SLL	-12.5 dB



(a) H-plane



(b) E-plane

Figure 19: Beam steering patterns of 9-element double layered Vivaldi antnna linear array at different steering angles in the principal planes.

CONCLUSION

This paper presented a design of a double layered tapered slot antenna for AESA radar applications. The antenna with complete size of 14.2x24.1x1.4 mm^3 and is capable of achieving approximately 10% bandwidth at X-band experimentally. The measured results of single element have shown a widebeam width and a gain of around 4dBi over X-band frequency in an array environment. The linear array composed of 9-element linear array and a 9-way T-junction power divider. The power distribution among the radiating elements is realized using a uniform distribution. The 9-element array was fabricated and measured over X-band frequency. The radiation performances of the array are good for the full scan area $\pm 60^{o}$. The designed antenna element is suitable for X-band airborne active phased array radars in combat aircraft.

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