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VIVALDI ANTENNA SIMULATION ON DEFINING PARAMETERS, PARAMETRIC STUDY AND RESULTS

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Abstract: Now a days the ultra-wide band antenna (UWB) is widely used in different applications such as microwave imaging, wireless communications, remote sensing and in biomedical field. In this paper a parametric study and design of the Vivaldi Antenna has been taken with the aim of reducing beam width, improving directionality and effective impedance matching of microstrip feedline to slot line. A computer aided design of Vivaldi Antenna is developed which is used to study the effect of different parameters such as rate of opening of exponential slot and size of the radius of circular slot on the performance of the Vivaldi Antenna. The study shows the key features that affect the VSWR, Directionality, Beamwidth and Side Lobes pattern. The overall performance is optimized by judiciously evaluating the equivalent circuit diagram, parametric and impedance equations. The design is first simulated at X band frequency on COMSOL Multiphysics software, after that the précised design is fabricated on PCB using FR4 substrate having dielectric constant 2.33 and fabricated design is tested on VNA. The simulation and experimental results show that the VSWR is -24.5dB at a frequency of 7.56 GHz.

Key Words: Vivaldi Antenna, Comsol Multiphysics, PCB Prototype Machine, SMA Connector, Copper Plate (FR4, 2.33 dielectric value), VNA.

1. INTRODUCTION

The Vivaldi antenna belongs to the class of antenna structures which are defined as aperiodic continuously scaled travelling wave. It is first recognized by Gibson [2] in 1979. Vivaldi antenna shows marvelous advantages in the field of efficiency, high gain, wide bandwidth and simple geometry.

The Vivaldi antenna is a special kind of tapered slot antenna (TSA), having an exponentially tapered slot profile. The Vivaldi antenna comprises of mainly the ground plate which is FR4, dielectric substrate and microstrip transmission line as feeding [2]. This antenna comprises of three different type of slotlines which are:

(i) **The circular slot** which is used to realize the impedance matching of the microstrip transmission line.

(ii) **The rectangular slot** which is used to couple the electromagnetic wave from the microstrip transmission line.

(iii) **The exponential tapered slot** which is used to guide the electromagnetic wave to radiate.

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The structure is somewhat similar to fan like structure which is used to realize the terminal load matching. Generally, the cut-off wavelength at low frequency of the Vivaldi antenna is about twice the maximum width of the exponential tapered slot, and the radiation performances at high frequency of the Vivaldi antenna is restricted by the minimum width of the exponential tapered slot. The Vivaldi antenna shows end-fire pattern.

2. LITERATURE SURVEY

For quick understanding of the following work, first step is to take a view on the work done previously.

Lewis [3] experimented a tapered slot antenna in 1974. In 1979 Gibson introduced a new type of TSA i.e. Vivaldi Antenna. It shows significant gain and linear polarization in a frequency range 2-18 GHz. Vivaldi antenna is fed by an asymmetric microstrip constructed on alumina using microwave photolithographic thin film techniques. Yngvesson [4] compared three different TSAs, linearly tapered slot antenna (LTSA), constant width slot antenna (CWSA) and Gibson's exponentially tapered slot antenna, Vivaldi antenna. Yngvesson found that Vivaldi antenna had the smallest side lobe levels followed by CWSA and LTSA whereas it had the widest beamwidth and CWSA had the narrowest one. He also investigated the effect of dielectric substrate thickness and the length of Vivaldi antenna on the beamwidth. E. Gazit [5] proposed two important changes to the traditional Vivaldi design. He used a low dielectric substrate (cuclad, _=2.45) instead of alumina and an antipodal slotline transition. The antipodal slotline transition was constructed by tapering the microstrip line through parallel strip to an asymmetric double sided slot line. This type of transition offered relatively wider bandwidth which was restricted by the microstrip to slotline transition of the traditional design. However, antipodal slotline transition had the problem of high cross polarization. Langley [6] improved the antipodal transition of E. Gazit with a new and balanced structure in order to improve the cross polarization characteristics. This type of structure, known as balanced antipodal transition, consists of three layers of tapered slots fed directly by a stripline. E-field distribution of the antipodal transition is balanced with the addition of the mentioned layer. The tapered slots on both sides of the antenna serve as ground planes. The balanced antipodal transition offered a 18:1 bandwidth with fairly well cross polarization characteristics. Langley [7] also constructed a wide bandwidth phased array using this balanced antipodal Vivaldi antenna. He achieved good cross polarization levels as well as wideband wide angle scanning. Kim [8] placed the antipodal antenna and its mirror image alternately in the Cross-polarization. The cancellation of cross polarization fields was aimed in this study and more than 20 dB reduction of cross polarization level at broadside was obtained. Schuppert [9] came up with circular stubs applied to microstrip to slotline transitions in order to offer an easier fabrication. Sloan [10] used radial stubs instead of circular ones and improved the bandwidth of these kind of transitions. Schaubert [11] used both circular and radial stubs in order to design a stripline-feed, metal fins placed on both sides of Vivaldi antenna. He stated in his study that 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 circular stripline and slotline stubs. It was also shown in this study that the stripline feeding increased the antenna bandwidth compared with the microstrip feeding.

3. METHODOLOGY

The steps to design a Narrow Beam Antenna and to characterize the outputs are as follows:

(i) Simulation of different Narrow Beam Patterns using COMSOL Multiphysics

(ii) Parametric studies on the proposed structures.

(iii) Fabrication of the structure.

(iv) Testing of results.

4. VIVALDI DESIGN

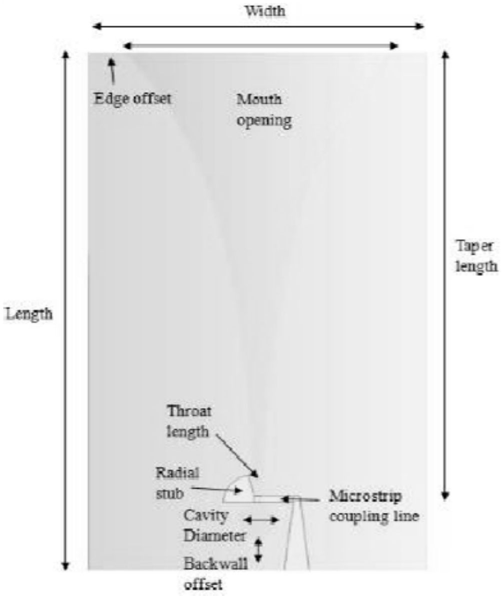


Figure 1 Vivaldi Antenna Structure

4.2 Parametric Effect on Vivaldi

Substrate

The design of the substrate can be considered in terms of its dielectric constant and thickness.

- **Dielectric constant:** The use of higher dielectric constant substrate shrinks the antenna dimensions. Besides, the use of a substrate with a lower dielectric constant provides wider bandwidth [15]. The trade-off between dielectric constant, dimensions and bandwidth needs careful consideration.
- **Thickness:** The thickness of the substrate is the other important design parameter. Normally, the use of a thicker substrate improves antenna performance in terms of gain and main beamwidth due to the decrease in antenna reactance [16]. In this, a FR4 substrate is used. This substrate is also the most commonly used PCB board which is cheap and easily fabricated.

Cavity Diameter

A circular cavity is added to the end of the slotline, as shown in Fig 4.1. The use of the cavity offers the freedom to tune the impedance matching [11], and this, affects the bandwidth of the Vivaldi antenna.

Taper

Taper design is based on two parameters: taper length and taper rate. The taper length should be on the order of one wavelength in the lowest working frequency [17]. Besides, the taper length is also dependent on the cavity diameter and antenna length. An increase in the taper length improves the bandwidth. The taper rate can be defined by an exponential.

$$Y = C1\, e^{Rx} + C2$$

Where $C1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}}$; $C2 = \frac{e^{Rx_2} y_1 - e^{Rx_1} y_2}{e^{Rx_2} - e^{Rx_1}}$

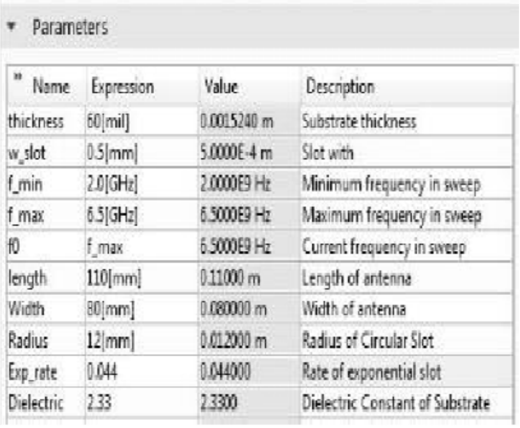
where R is the taper rate x_1, x_2, y_1 and y_2 indicate the slotline start and end points

Backwall Offset

The backwall offset is the extension metallization between the cavity and the edge of the antenna. The use of the backwall offset prevents the abrupt end of the current flow and thereby offering the freedom to tune the bandwidth [11].

Designing Parameters

General parameters that are used during the design of Vivaldi Table 2.1 Parameters Values Antenna:


▾ Parameters

Name	Expression	Value	Description
thickness	60[mil]	0.0015240 m	Substrate thickness
w_slot	0.5[mm]	5.0000E-4 m	Slot with
f_min	2.0[GHz]	2.0000E9 Hz	Minimum frequency in sweep
f_max	6.5[GHz]	6.5000E9 Hz	Maximum frequency in sweep
f0	f_max	6.5000E9 Hz	Current frequency in sweep
length	110[mm]	0.11000 m	Length of antenna
Width	80[mm]	0.080000 m	Width of antenna
Radius	12[mm]	0.012000 m	Radius of Circular Slot
Exp_rate	0.044	0.044000	Rate of exponential slot
Dielectric	2.33	2.3300	Dielectric Constant of Substrate

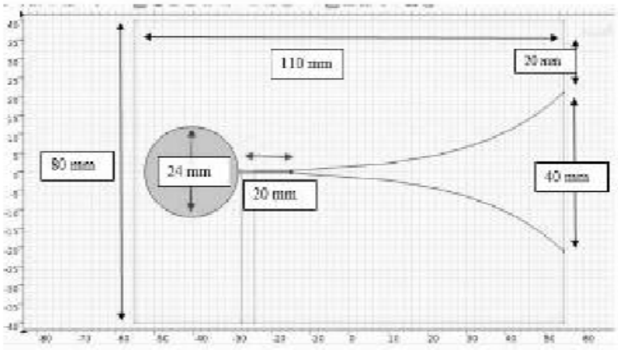


Fig 2 Vivaldi Antenna dimension

- **Antenna Length:** Antenna length should be greater than the average value of the maximum and minimum operating frequency [2, 11].

  F_{max} =6GHz; F_{min} =2 GHz; $\lambda = \frac{c}{f}$;

  λ_{min} =50mm ; λ_{max} =150mm ; so L is taken 110 mm.

  $L > \frac{\lambda\text{min}+\lambda\text{max.}}{2} = \frac{50+150.}{2} = 100mm$;

- **Antenna Width:** Antenna width should be greater than half of the average value of maximum and minimum operating frequency [2,11].

  $W > \frac{\lambda\text{min}+\lambda\text{max.}}{4} = \frac{50+150.}{4} = 50mm$; so W is taken 80 mm.

- **Mouth opening:** There is a bound on the value of opening width [11].ie. mouth opening should have a value in between Wmin and Wmax.

  $W_{min} = \frac{\lambda g}{f.\varepsilon}$ and $W_{max} = \frac{\lambda g}{2}$

Calculation

$$\lambda_g = \frac{c}{\text{fmin}.\sqrt{\varepsilon}} = \frac{3\times10^8}{2\times10^9\times\sqrt{2.33}} = 98\text{mm}$$

$W_{\max} = \frac{\lambda g}{2} = \frac{98}{2} = 49$ mm and $W_{\min} = \frac{\lambda g}{f.\varepsilon} = \frac{3\times10^{8}}{5\times10^{9}\times\sqrt{2.33}} = 39$mm

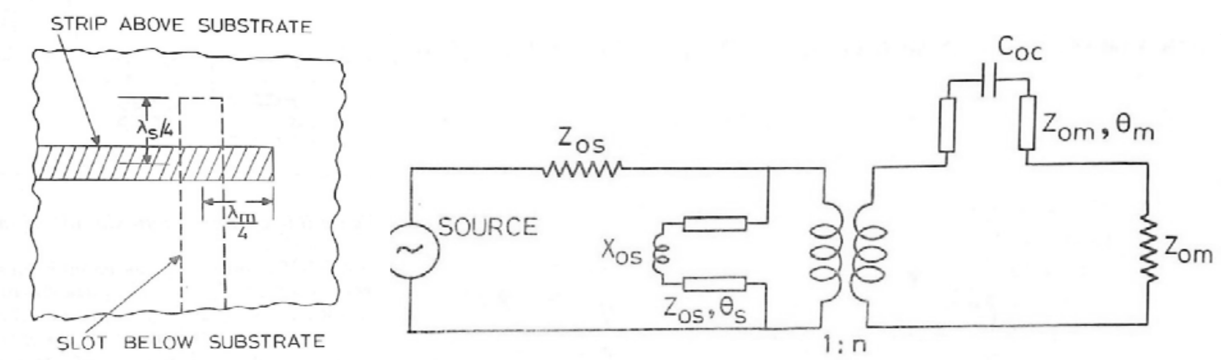
where, c = speed of light (3 x 108); *f* min = frequency minimum (2GHz); ε = dielectric constant (2.33)

Wmax=49 mm; Wmin=39 mm. Hence an optimum width value is taken i.e. 40 mm.

- **Throat Length:** Throat length is taken 20 mm.
- **Edge offset:** Edge Offset value is 20 mm.
- **Cavity Diameter:** Cavity diameter is taken as 24 mm.
- **Backwall Offset:** Backwall offset value is 2.5 mm.

4.3 Microstrip to Slotline Transition

A microstrip-slot transition is shown in fig. 4.3.1(a) [13]. The slotline which is etched on one side of substrate is placed at right angle to a microstrip conductor on opposite side. The microstrip extends about one quarter of a wavelength beyond the slot and similarly, the slot extends about one-quarter of wavelength beyond the microstrip. The microstrip part of the circuit can be placed on one side of the substrate and the slotline part on the other side.



(a) (a)

Fig. 3 (a) Microstrip line to slotline (b) Equivalent circuit diagram of Microstrip line to slotline

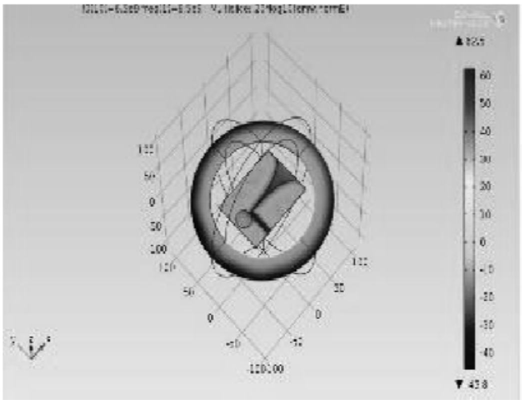
An equivalent circuit of microstrip transition is shown in fig. 4.3.1(b) [12]. The reactance X_{OS} represents the inductance of a shorted slotline and C_{oc} is the capacitance of an open microstrip. Z_{OS} and Z_{OM} are slotline and microstrip impedances respectively. θ_s and θ_m represent the electrical lengths of the extended portions of the slotline and the microstrip. Depending on the dimensions of the transmission line the characteristic impedance Z_0 can be calculated.

For $W/h \leq 1$, $$Z_0 = \frac{60}{\sqrt{\varepsilon_e}} \ln\left(\frac{8h}{W} + \frac{W}{4h}\right)$$

For $W/h \geq 1$, $$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_e}\left[\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h} + 1.444\right)\right]}$$

4. SIMULATION

The whole modelled domain is surrounded by a perfectly matched layer (PML) Fig5.1. PML functions as an anechoic chamber which absorbs all of the radiated energy beyond that layer. After simulating and solving the antenna model using COMSOL Multiphysics, the results are studied in various forms. The SWR plot reveals that the model has good wide-band impedance matching as shown in figure 5.2.



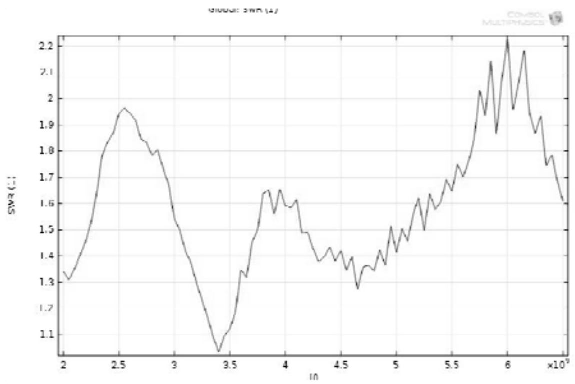
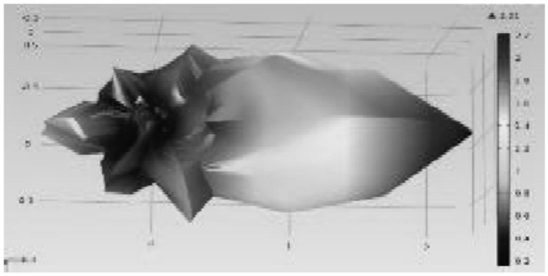


Fig 4 Far-filed plot of Vivaldi Antenna

Fig 5 SWR plot



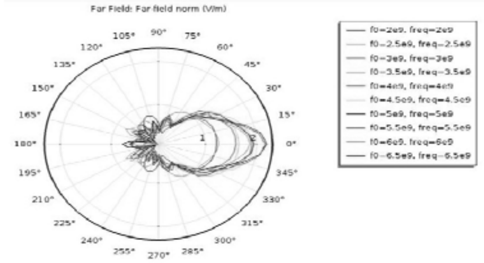


Fig 6 Lobes plot

Fig 7 Polar Plot

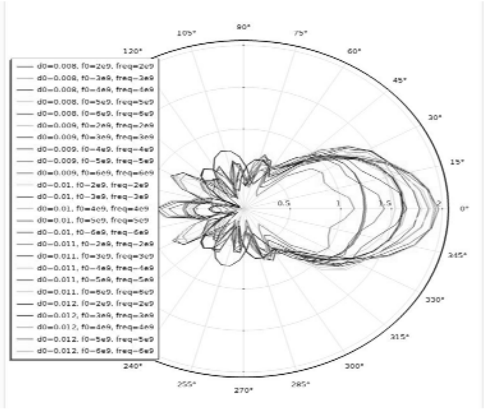
5.1 Discussion of Results

At 4.8GHz the SWR obtained is 1.27 which results in a Reflection Coefficient of 0.118 which is equal to 18.49 dB. The Beamwidth is plotted against a frequency range of 2GHz to 6GHz. According to the obtained polar plot the minimum beamwidth is obtained at a frequency of 5.5 GHz. The corresponding values for SWR is 1.45 and Reflection Coefficient is 0.183 equals to -14.71 dB.

6. PARAMETRIC STUDY

Variation of the Diameter of the Circular Slotline Cavity:

The cavity offers the freedom to tune the impedance matching [14], which affects the bandwidth of the Vivaldi antenna. The effects of the circular slotline cavity are studied by keeping the other parameters fixed.



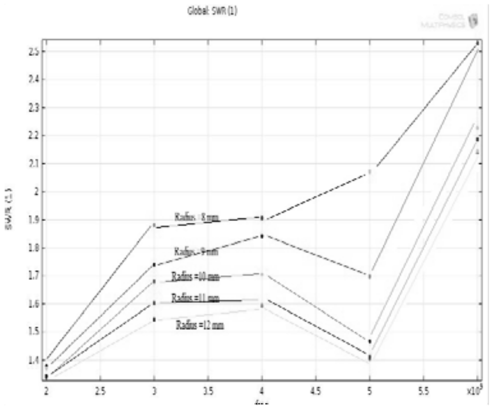


Fig 8 Polar plot for cavity diameter variation

Fig 9 SWR plot for different cavity diameters

The radius of the slotline is varied from 8mm to 12 mm. From the simulated results, it is verified that antenna shows high directionality and effective impedance matching at a frequency of 5GHz. At this frequency beam width as well as SWR is seen to be minimum as shown in fig. 6.1.1 and fig. 6.1.2 respectively.

Discussion of Results:

The antenna is simulated at different radius of circular slot. The exact behavior of Beamwidth pattern and SWR values can be easily interpreted from above shown figures i.e. fig. 6.1.1 and fig 6.1.2 which clearly shows that there is an inverse relationship between the Circular Cavity Radius and SWR value. Increase in radius of slot results in lower SWR value. It is also seen that minimum beamwidth is obtained at 12mm cavity radius.

Exponential Opening Rate Variation:

Exponential slot is guided by the following equation. y= $\pm c_1 e^{Rx} + c_2$; where c_1 and c_2 are calculated by using the end points in above equation. The opening rate of the tapered slotline affects mainly the mid-band performance of the TSA. In this section, exponential slot rate is taken as 0.044*x; where 'x' is multiplying factor which is being varied from 0.25 to 1.

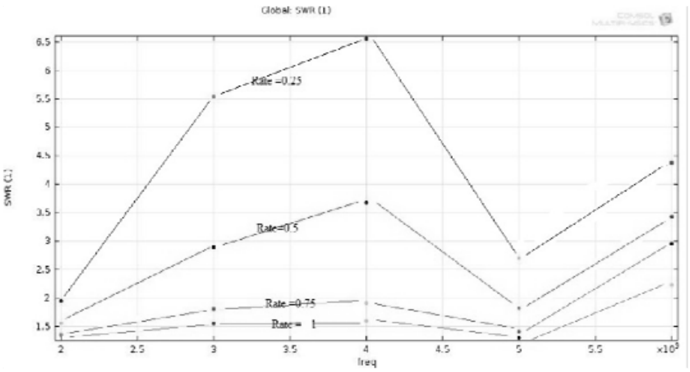


Fig 10 SWR plot for different exponential rate

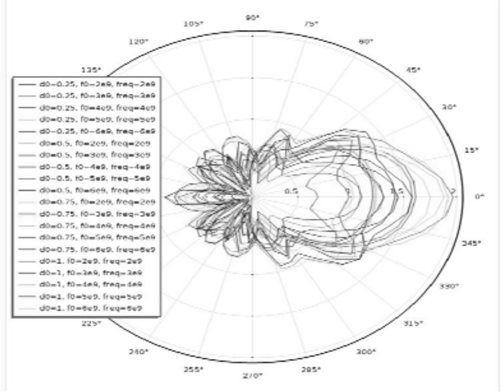


Fig 11 Polar plot for different exponential rate

Discussion of Results:

From the above figure it is observed that as the rate of exponential slot increases there is a wide increase in the beam width of antenna. The wave guides along the exponential slot. Hence it can be concluded that beamwidth is dependent on the rate of exponential slot.

7. VIVALDI IMPLEMENTED ON PCB FR4 SUBSTRATE

After studying all the different parametric effects on antenna performance, a précised design is used to fabricate the antenna. Two different type of structures are studied in this context i.e. the rectangular geometry and the trapezoidal geometry of antenna. From the experimental result it is observed that the trapezoidal geometry provides a better VSWR in comparison to rectangular geometry. Type 1 antenna shows VSWR equals to -17dB at a frequency of 7.83 GHz whereas type 2 antenna shows a VSWR equals to -24.5dB at a frequency of 7.56 GHz. From the results it can be interpreted that there is a slight shift in frequency which occurs due to the change in geometry.

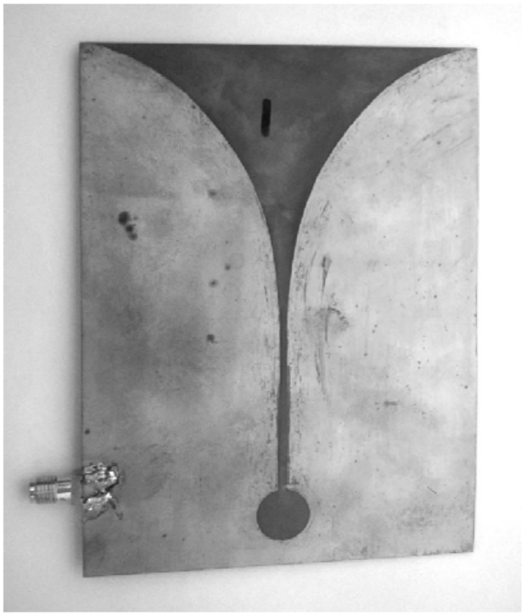


Fig 12 Antenna Type 1 (Rectangular Geometry)

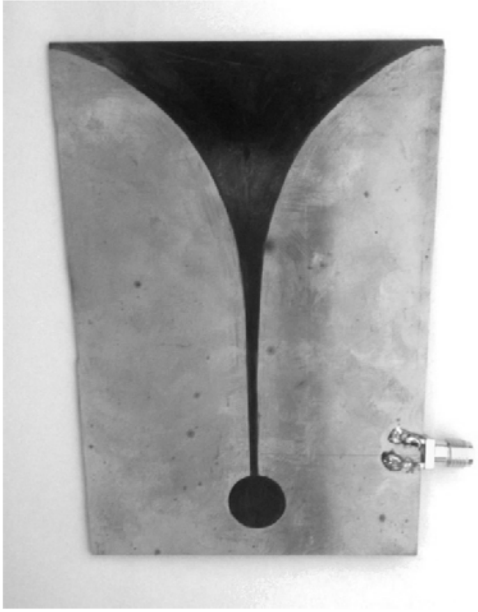


Fig 13 Antenna Type 2 (Trapezoidal Geometry)

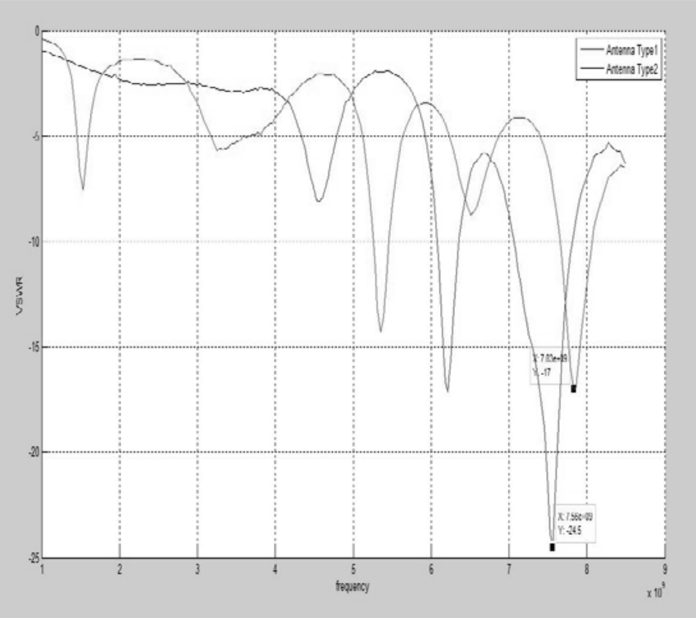


Fig 14 VSWR Plot for both type of Antennas

8. CONCLUSION

The Vivaldi antenna observed in this report is a type of TSA with its exponentially tapered profile, is observed in this report. As a member of the class of TSA, Vivaldi antenna provides broad bandwidth, low cross polarization and directive propagation at microwave frequencies.

This report presents the design and detailed results of the Vivaldi Antenna with the selection of FR4 substrate material. This antenna is showing remarkable performance at a frequency of 7.5 GHz and VSWR equal to-24.5dB with high directivity and narrow beamwidth.

9. FUTURE SCOPE

Vivaldi antenna has a large scope in biomedical. It can be designed for medical imaging which works inside the environment of matching liquid for better coupling of power from the antenna to the human tissues. However gain of the antenna is not uniform along the entire frequency range of operation. This is a potential area to work.

Further implementation of Vivaldi antenna having surface coated with metamaterial can provide a highly narrow beam width which will be very much effective for biomedical purpose.

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