Design of Antipodal Vivaldi Antenna in a Matching Medium for Microwave Medical Imaging

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***Abstract*—An Antipodal Vivaldi antenna design is presented for microwave imaging for medical applications. The antenna operates inside a suitable matching medium for the human body. A wide impedance bandwidth of operation has been achieved in the matching medium with a good value of gain along the entire bandwidth of operation. The antenna was designed using CST Microwave Studio simulator and the final results are verified by measurements. A good amount of similarity is observed in the simulated and experimental results.**

Keywords—*Vivaldi antenna, Antipodal Vivaldi Antenna, Microwave imaging, Microstrip, Slotline, Corrugations, Co-polarization, Cross-polarization, Beamwidth, Sidelobe level.*

I. INTRODUCTION

Microwave imaging has evolved at a very rapid pace in the last decade and has been applied to both medicine and industry [1]. Microwave Imaging employs the use of antenna and digital signal processing to generate images of objects and human body organs. Due to broadband characteristics and high directivity, the Vivaldi antenna [2] is very commonly used in microwave imaging applications. But the Vivaldi antenna employs the use of microstrip to slotline transition [3] which is very difficult to design effectively. The Antipodal Vivaldi antenna eliminates the problem of complex feeding network design of the classical Vivaldi antenna by using simple microstrip line feeding network.

II. SYSTEM ARCHITECTURE

The imaging of the human organs has to be done to detect position and size of tumor inside the body. The human brain is has a very complex dielectric profile with an average dielectric constant of around 55 [4]. So the antenna to be developed is to operate inside a suitable matching liquid. This matching liquid medium will reduce the reflection from the head when compared to free space making the system power efficient. Also reducing the amount of reflection at the boundary of the head and will help in increasing the purity of reflected signal from the brain which will be received by the antenna. Immersing the antenna inside the liquid will reduce the dimensions of the antenna when compared to free space by a factor of square root of dielectric constant of the matching liquid. The matching liquid used in this design is 1:1 mixture by volume of ethyl alcohol and water. It gives a dielectric constant value of 52 under standard room temperature and pressure [5], in the frequency range from 500 MHz to 5 GHz.

This frequency range has been selected for operation because of two reasons. Firstly lower is the frequency greater will be skin depth of the electromagnetic signal into the human tissue. This is very essential for imaging of tumor cells which may be deeply located inside the brain. The second reason of selecting a large bandwidth extending to 5 GHz is to increase the information carrying capacity of the signal which will help to generate images of high resolution and accuracy.

A systematic procedure was employed in the design of the antipodal Vivaldi antenna. Almost all the design parameters are studied with respect to their physical significance in the antenna performance. A substrate of size 45mm×24mm with ε_r= 10.2 (ROGERS 3010) was used. The antenna will operate inside the matching liquid of $\mathcal{E}_r$= 52.

III. ANTENNA DESIGN

The basic structure of the Antipodal Vivaldi (AV) antenna is shown in figure 4.1.

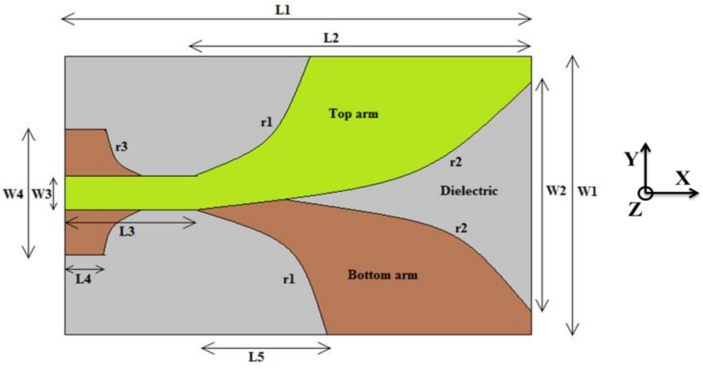


Fig.1:Schematic of Antipodal Vivaldi antenna

In this work the faring of the arms of the AV antenna are designed exponentially as:

$$f(x) = c_1 * \exp(r * x) + c_2 \qquad (1)$$

where r is the curvature parameter and the constants c1 and c2 are constants which are mathematicallycalculated for each curve. For any given curve passing through the points (x_1, y_1) and (x_2, y_2)they are defined as

$$c_1 = \frac{y_2 - y_1}{\exp(r * x_2) - \exp(r * x_1)} \qquad (2)$$

$$c_2 = y_2 - c_1 * \exp(r * x_2) \qquad (3)$$

IV. ANTENNA PARAMETERS

1. *Bandwidth of operation*:From the analysis of the current distribution over the radiator plates it isinferred that at the edges of the conductor plate the current concentration is much higher than thatin the middle.It leads to the conclusion that the inner edges of the radiating arms are actually responsible forradiations. It is desired that the current density through the inner curve should be as high as possible.Due to tapering nature of the curves, the distance between the radiating arms increases withincreasing distance from the feed. So these parts are responsible for radiation of lower frequencysignals. To achieve the lowest possible radiated frequency it is necessary to ensure that the largestdistance between the two arms corresponds to half of its corresponding wavelength.

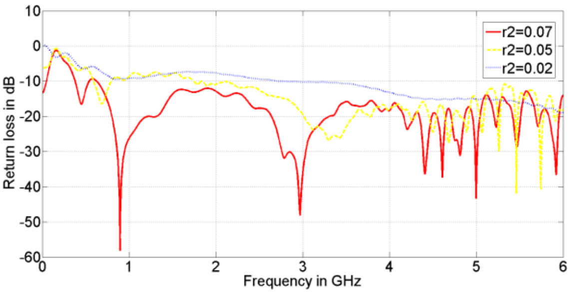


Fig 2: Return loss plot for different values of r2

The return loss results (see Fig. 2) of the design with r2 = 0.07 is not satisfactory as faras the lower cut-off frequency range is concerned. The lower cut of frequency is at 2.72 GHz. Butthe requirement of this design is a lower cut-off frequency of about 500MHz. Thus there is a needto decrease the lower frequency of operation. This can only be achieved by varying the shape ofthe inner exponential curves. Therefore the slope of the inner curve (r2) is varied to change theminimum frequency of radiation from the structure. Finally a value of r2 is determined throughparameter sweeping and the desired plot of return loss vs frequency is achieved. Another importantfeature to be mentioned is that varying the parameter r2 has negligible effect on other results (gain,efficiency, etc.) of the design except the bandwidth. From the plot of return loss vs. frequency fordifferent values of r2 (from Fig. 2) it is proved that the inner curves control the bandwidth ofoperation of the antenna. Finally at r2 = 0.07, the -10 dB impedance bandwidth is achieved from600MHz to 5 GHz.

2. *Sidelobe level*: The surface current of Vivaldi antenna not only distributes around the inner exponentially taperedslot but also flows through the outside borders of metal arms. It can be verified from the simulationresults that there is a considerable surface current flowing along the outer edge of the metallizationto the back-end part of antenna, especially in lower frequency range. Since the total radiationpattern is superposition of the radiation from current flowing on both inner and outer edge of themetal arms, thus the outer edge current contributes to an unwanted side radiation that result inreduction of the antenna's gain.

In order to increase the gain in lower frequency range, the outer edges of the metal arms are corrugatedwith a set of rectangular gratings [6], which create a high-impedance structure in thepath of the current flow from the mouth of the antenna to the back end of the structure (see Fig. 3). This helps to reduce unwanted lateral radiations.

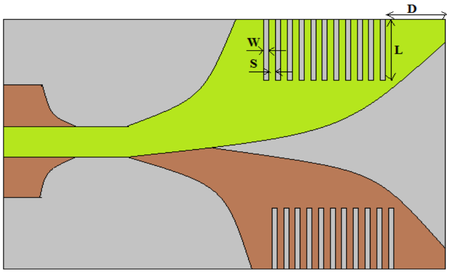


Fig. 3: Design of high impedance rectangular corrugations

Table 1: Design parameters for rectangular corrugations

Parameters	Physical Description	Dimensions
W	Width of each corrugation	1 mm
S	Spacing between each corrugation	1.5 mm
L	Length of each corrugation	5.36 mm
D	Distance of first corrugation from mouth of antenna	5mm
N	Number of rectangular corrugations	11

As evident from the results in table 1 the introduction of the high impedance corrugations has successfully led to reduction in side lobe level (see table 2). The decrement in side lobe level is very essential for the design.

Table 2: Design parameters for rectangular corrugations

Frequency in GHz	SSL without rectangular corrugations in dB	SSL with rectangular corrugations in dB
0.5	-6.5	-7.83
1	-5.32	-8.7
2	-10.62	-11.55
3	-10.76	-11.82
4	-15	-15.97
5	-8.91	-11.3

3. *Co-polarization and Cross-polarization*: The skew nature of E-field (see Fig. 4) from top metallic arm to the lower metallic arm increasescross-polarization.

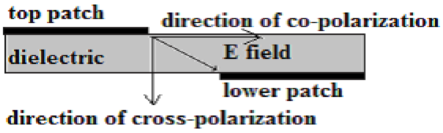


Fig. 4: E-field distribution between metallic arms of the AV antenna

The cross-polarization is severe for higher frequencies. This is because thelower frequencies get radiated from the mouth of the antenna where the lateral distance between theupper and lower arms is increased and correspondingly there is a decrease in skewnessof the E-field.

This feature of the Antipodal Vivaldi antenna cannot be removed entirely but can be decreased bysome modification in the antenna design. The only way to decrease the amount of cross polarizationis to decrease the skew nature or the slope of the E- field from the top arm to the lower arm. Thisdecrease in slope of E-field direction will decrease the cross-polarization component. The solutionto this problem is to decrease the height of the substrate of the antenna. Decreasing the height ofthe substrate will increase the co-polarization and decrease the cross-polarization components.

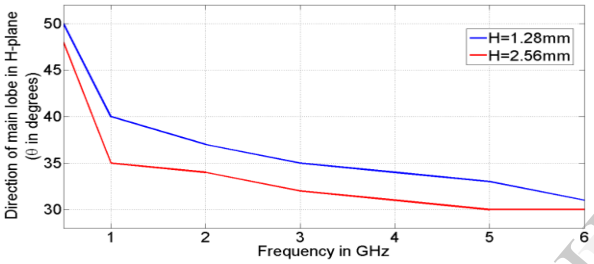


Fig. 5: Comparison of direction of main lobe in H-plane for different substrate height.

In the H-plane (XY plane, $\theta = 90^0$) the desired main beam of radiation is at $\theta = 90^0$, $\varphi = 0^0$. But dueto cross-polarization component the main lobe is shifted from the desired direction. As expectedthe amount of shift of the main lobe from $\theta = 90^0$ increases as frequency of radiation is increaseddue to increase of cross-polarization component. From Fig. 5 it is clear that the shifting ofthe main lobe of radiation is getting increased from the desired direction ($\theta = 90^0$) as frequencyis increased. The maximum shift from the desired direction ($\theta = 90^0$) observed at 6 GHz is $60^0$and 59^0 for height of substrate H = 2.56 mm and 1.28 mm respectively. So the shift of main beamtowards the desired direction is decreased by 1^0 when the height of substrate is decreased from 2.56mm to 1.28 mm. The difference of shifting of main lobe is less at lower frequencies. At 0.5 GHzthe shift is 40^0 for H = 1.28mm and 42^0 for H = 2.56 mm. So the main lobe has shifted by 2^0 awayfrom the desired direction when the height of substrate is increased from 1.28 mm to 2.56 mm.

4. *Gain*: The outer curves of the top and bottom metal arms influence the main lobe beamwidth and thegain. The current flow along this path is responsible for this property.

Thus by changing the valueof exponential slope of the outer curve (r1) the gain of the antenna can be increased and a highlydirective beam can be obtained.The value of gain for r1 = 0.1 is more than that for r1 = 0.3 (see Fig. 6). But the gain is uniformalong the entire band of operation for r1 = 0.3.

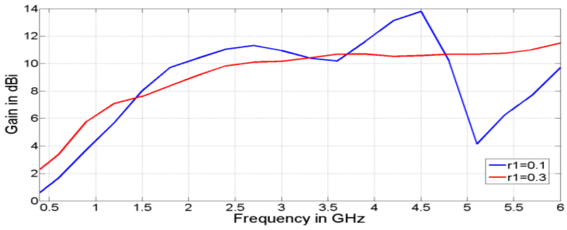


Fig. 6: Comparison of gain for different values of r1

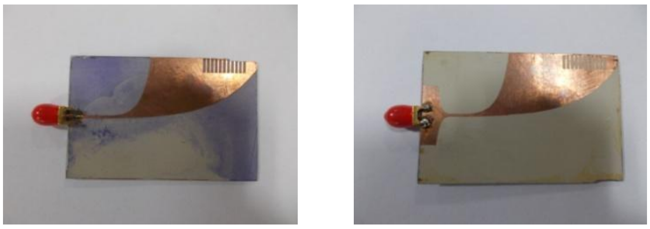
V. RESULTS AND DISCUSSIONS

The final optimized antenna dimensions are given in Table 3.

Table 3: Final design parameters of AV antenna

Parameters	Physical Description	Dimensions
L1	Total length of substrate	70 mm
L2	Length of inner flaring	55 mm
L3	Length of microstrip line feeding	15 mm
L4	Length of ground plane	5 mm
L5	Length of outer flaring	15 mm
W1	Total width of substrate	45 mm
W2	Width of mouth opening	40 mm
W3	Width of microstrip line feeding	0.85 mm
W4	Width of ground plane	20 mm
r1	Exponential slope of outer arm	0.3
r2	Exponential slope of inner arm	0.07
r3	Exponential slope of ground plane tapering	-1
L	Length of rectangular corrugation	5.36 mm
W	Width of rectangular corrugation	1 mm
S	Spacing between rectangular corrugation	1.5 mm
D	Distance of first corrugation from antenna mouth	5 mm
N	Number of rectangular corrugations	11
H	Thickness of substrate	1.28 mm

The antenna design was fabricated (see Fig. 7) according to the dimensions mentioned in table 3.



(a) Top view (b) Bottom view

Fig.7: Fabricated Antipodal Vivaldi antenna

The matching liquid is prepared by mixing water and ethyl alcohol in 1:1 ratio by volume. The measurement of return loss is done by immersing the antenna. The measurement setup is shown in Fig. 8. The return loss characteristic of the final AV antenna is shown in Fig. 9.

Fig. 8: Measurement setup

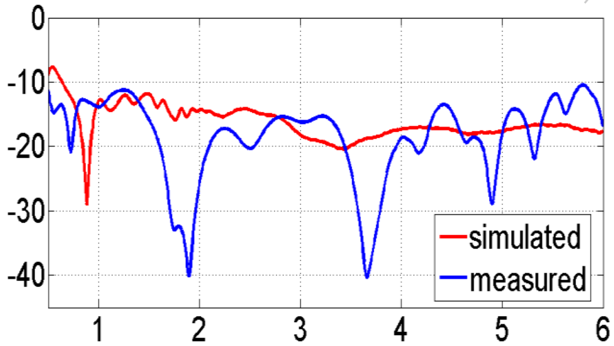


Fig 9: Return loss characteristics of the final AV antenna

There is a slight variation between simulated and measured return loss parameter. But the overall results are satisfactory. The S11 is around -15 dB from 500 MHz to above 5 GHz. So the design goal as far as impedance bandwidth is concerned is achieved successfully.

A directive beam is achieved in both E-plane and H-plane. But due to inherent cross-polarization property of AV antenna the main lobe of radiation is shifted from the desired direction in the H-plane. However in near field microwave imaging this deflection of the main beam can be considered.

VI. CONCLUSION AND SCOPE OF FUTURE WORK

An Antipodal Vivaldi antenna was designed for medical imaging which is working inside the environment of matching liquid for better coupling of power from the antenna to the human tissues. The simulation of the design inside the matching liquid is done using CST Microwave Studio 13. The verification of return loss results is done by hardware implementation of the system. The achieved bandwidth of operation is from 500 MHz to 5 GHz with an average gain of 8 to 10 dBi. However gain of the antenna is notuniform along the entire frequency range of operation and degrades to a very low value of 3.5 dBiat 500MHz.This is a potential area of future work. But the major limitation of the Antipodal Vivaldi antenna is the cross-polarization due to which the structure is generates a deflected directive beam from the aperture of the antenna.

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