INDIAN INSTITUTE OF SCIENCE, BANGALORE

Supercomputer Education and Research Center

NMIT, Bangalore

Department of E & C

STUDY OF WIDEBAND ANTENNAS

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Indian Institute of Science, Bangalore

SUMMER RESEARCH FELLOWSHIP PROGRAM-2014

FINAL REPORT

INDIAN ACADEMY OF SCIENCE, BANGALORE

INDIAN NATIONAL NATIONAL SCIENCE ACADEMY, NEW DELHI

NATIONAL ACADEMY OF SCIENCES, ALLAHABAD

JUNE-JULY 2014

Summer Research Fellowship Program-2014
Project Approval Certificate

Supercomputer Education and Research Center

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This is to certify that the Project entitled, "**Study of Wide Band Antennas**" is a record of bonafide work carried out by **Mr.Kamal Lamichhane**, a student of Nitte Meenakshi Institute of Technology, in fulfillment of the completion of Summer Research Internship conducted by the Indian Academy of Sciences during June-July 2014. The work has been carried out at Supercomputer Education and Research Center, Indian Institute of Science, Bangalore. It is certified that all the corrections and suggestions indicated during the course of two months have been incorporated in the report. The project report has been approved as it satisfies the requirement in respect of project work.

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Place: IISC, Bangalore
Date: July, 2014

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and ref erenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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31^{st} –July-2014

ACKNOWLEDGEMENT

I profoundly grateful to my Project Guide **Prof. N. Balakrishnan, Professor and Associate Director, Indian Institute of Science** for his expert guidance & continuous encouragement throughout the project providing all the necessary resources for this project. A deep sense of gratitude to **Indian Academy of Sciences** for providing me this platform to work at IISC. I would like to express my gratitude to **Prof. N R Shetty, Director, NMIT** and **Dr. H C Nagaraj, Principal NMIT** for their continuous support.

I would like to thank **Dr. S.Sandya, Head of Department**, Electronics & Communication engineering department and all the staff members of **E&C Department, NMIT** whose invaluable guidance supported me in completing this project.

A deep sense of gratitude to **Mr. Yogindra Negi, Scientific officer** and **Mr. Venkat Prasad Padhy,** PhD Scholar, **Electromagnetics Lab, SERC IISC**, for their support and guidance for the successful completion of this project.

At last I must express my sincere heartfelt gratitude to all the staff members of **Supercomputer Education and Research Center, IISC** who helped me directly or indirectly during this course of work.

I would like to extend a word of thanks to all my friends who have made my stay in IISc a pleasant and memorable one. I like to thank my parents, whose unlimited love and support has made this effort possible. Finally, I thank Almighty God for always being there to guide me through thick and thin.

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ABSTRACT

There has been tremendous demand for antennas occupying a small volume in wireless communication applications to reduce cost and increase mobility. Furthermore, because a single antenna is preferred to handle multiple bands and radios, wider operating bandwidth of the antenna also becomes important. A small size antenna is required with a wide operational bandwidth, but without sacrificing radiation efficiency or gain. The narrow band antennas may individually be used for either line of sight or beyond line of sight application, whereas wide band antennas cover both the bands and single antenna can be used with suitable beam forming circuitry. So, requirement of frequency independent, wide band single antenna is increasing day by day with the high data rate transmission requirement.

In this report, I have discussed the design procedure of various wideband antennas including results of simulations and optimization methods along with their application efficiency. Four Wide-Band Antennas named Vivaldi Antenna, Sinuous Antenna, Multi-arm Spiral Antenna, and Microstrip Multi-arm Spiral Antenna. Particularly, these antennas can be used in aircraft structure to achieve the high data rate transmission along with high directive gain and low return loss. Designed antenna will be able to track and communicate with the communication base station throughout and will be able to minimize the effect of jamming by introducing a null in the direction of arrival of jamming signal. The requirement of low profile and low RCS antenna is achieved with this work. This work includes parametric study and design of wide-band antennas. The parameters of single element antennas are investigated regarding their effects on the design. The return loss responses and radiation patterns are considered in the parametric study. The results of simulations realized using Feko, electromagnetic field simulation program, are shown and discussed.

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1. Introduction

1.1 Motivation

Wireless communication technologies continue to evolve and expand at the phenomenal place. Third-generation long term evolutions (3G-LTE) systems, Cognitive radio technologies (CR) for efficient use of spectrum, and wireless broadband connectivity to the mobile users have been the major focuses of recent research and standardization. Wideband antennas are widely used in many applications such as aircrafts, ground penetrating Radars, tracking, sensing and imaging, Multiple input multiple output system (MIMO), diversity operations, and robotics applications. To achieve the requirement of current revolution, various wide band antennas have been designed and documented.

Vivaldi antenna is a wideband antenna which is having taper slot radiator grown upon the dielectric. A strip line fed Exponentially Tapered Slot Antenna (ETSA) was proposed by P. J. Gibson in 1979, namely Vivaldi antenna[1]. The Vivaldi antenna was formed by widening the slot between two adjacent metal patches that supported by a thin dielectric substrate in a tapered exponential way. This antenna has a wide operating bandwidth and relatively high gain.

The sinuous antenna was originally conceived by DuHamel in 1982[2]. This particular antenna is broadband and capable achieving dual orthogonal linear or circular polarizations from the same aperture. The planar sinuous

[1] P. J. Gibson. The Vivaldi aerial [J]. 9th Europe Microwave Conference.1979. 101~105.
[2] R. H. DuHamel, "Dual Polarized Sinuous Antennas," U.S. Patent 4658262, April 14, 1987.

antenna is a bi-directional structure, radiating in both half- spaces. If one desires unidirectional operation from this planar structure, an absorptive material must be placed on one side of the aperture and is typically enclosed in a cavity. An alternative to this cavity backed design is to project the planar geometry onto a cone. The resulting structure radiates from a backward traveling wave and a high front-to-back ratio is the result, without any use of lossy material as with the planar structure.

The Multi-arm spiral[3] antenna is a wideband antenna with low profile and circular polarization. The frequency band of a spiral antenna depends only on the physical dimension of the antenna. However, spiral antennas require balanced feed structures and the input impedance of the spiral antenna can also vary from 140-200 Ω. Most standard feeders such as coaxial cables are unbalanced with 50 Ω input impedance. Therefore, balanced feeding structures which can also perform the impedance transformation are needed for spiral antennas. This antenna has also been utilized as a multifunction antenna for car where mode-0 is used for terrestrial communication and mode-1 is used for satellite communication[4].

Microstrip Spiral antenna is a recent variation on the conventional spiral antenna. The most desirable properties of this type of antenna is that it does not require a cavity backing behind the spiral. So, antenna will become thinner and lighter as compared to the conventional spiral antenna. This antenna also has been utilized as a multifunction antenna for car where the mode-o is implemented operational.

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[3] Four-arm spiral antennas, Corzine .R. G & J.A Mosko. 1990, Norwood, MA, ArtechHouse.

[4] Eberhard Gschwendtner and Werner Wiesbeck,"Ultra-Broadband Car Antenna For Communication And Navigation Applications", IEEE TRANASACTION ON ANTENNAS AND PROPAGATION,VOL. 51 NO. 8 AUG 2003

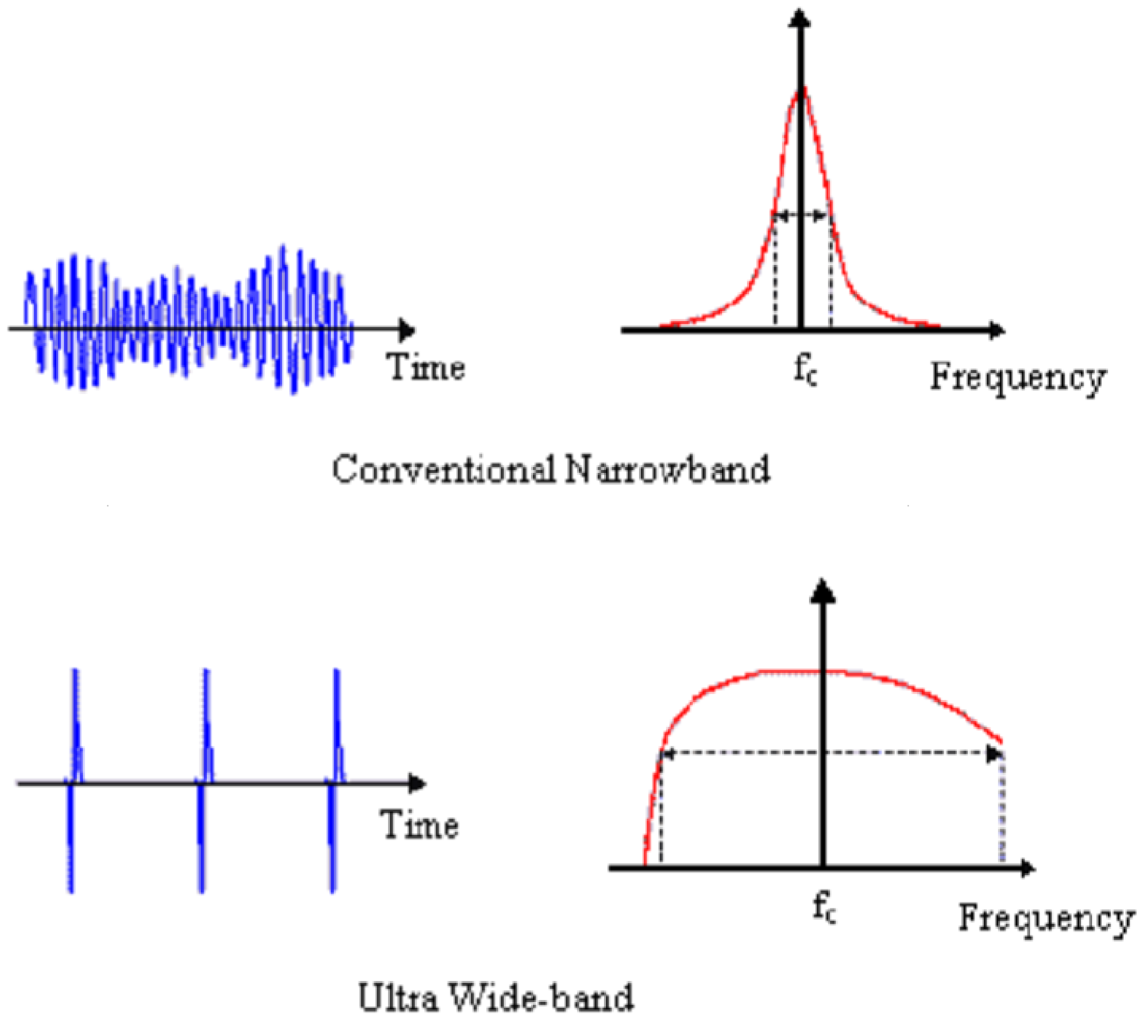


Figure 1.1-a Comparison of narrow-band and wide-band operation

The main objective of this research work is to design a wideband antenna for operation in high bandwidth ratio with a compact design. In presented report, four antennas have been designed and a simulation results have been discussed. In addition, spiral microstrip antenna[5] is optimized to operate in four different modes to realize a null in the given direction.

[5] Richard J.Barton, Peter J. Collins, Paul E.Crittenden, Miachel J. Havrilla, Andrew J. Terzuoli, "Acompact Passive Broadband Hexagonal Spiral Antenna Array for VHF Remote Sensing", IGARSS, page 593-595, IEEE, 2007

1.2 Contributions

Through the research work, following contributions have been made to the field of wide-band antennas. In this section a summary of these major contributions are presented:

- A comprehensive review of theory, principles and techniques of wide-band antennas and feeding techniques are presented.
- Vivaldi antenna is designed with the point source at the base of the exponential taper slot to achieve high gain and good bandwidth ratio to operate in the range of 300 MHz-3 GHz.
- Sinuous antenna is designed to operate in the frequency range of 300MHz -4 GHz without reflecting ground plane.
- Microstrip Spiral antenna is optimized to operate in four different modes of operation.

1.3 Organization

This report is organized into 7 sections. Section 2 contains a review of previous work related to different types of wideband antennas and antenna wideband properties such as radiation patterns, gain, polarization, impedance and band-width. A broad view of Vivaldi antenna along with its design specification and simulation results is presented in section 4. In section 5, 6 & 7, Multi-arm spiral and sinuous antenna are discussed along with the design specification and simulation results .All the simulation is done in FEKO[6].

[6] FEKO, Comprehensive Electromagnetic Solutions, S.A

2. Fundamental Properties of Wideband Antennas

2.1 Introduction

This research study provides an overview of wideband antennas, focusing specifically on the concept of Vivaldi antenna, sinuous antenna and spiral antenna with different element sizes. The performance of the antenna is determined by antenna parameters such as radiation patterns, gain, impedance, polarization and bandwidth of the antenna. This chapter describes all these antenna parameters and the related equations for the antenna design in detail.

Different types of wideband antennas such as Vivaldi antennas, sinuous antennas and spiral antennas are examined in following Section. Major focus of this research is the comparative study, simulation and analysation of various wide band antennas. Due to easy implementation with balanced devices, and wideband characteristics the Archimedean spiral antenna was found to be best as compared to other wideband antennas.

2.2 Antenna Properties

Important antenna parameters to be considered for wideband antenna designs include impedance matching, bandwidth, radiation patterns, gain, and directivity and radiation efficiency. These parameters are almost constant in the narrow band antenna, but can vary significantly in wideband antennas. These important antenna parameters are described in detail below.

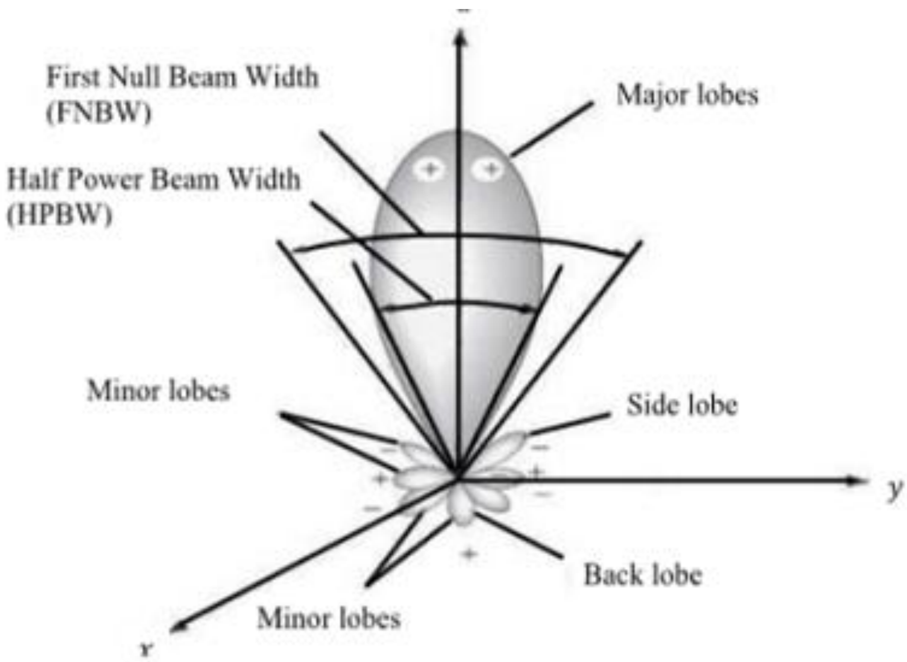
2.2.1 Radiation Pattern

An antenna radiation pattern is defined as a graphical representation or a mathematical function of the radiation properties of the antenna as a function of space coordinates. It is mostly determined in the far field region and is represented as a function of the directional coordinates. Radiation properties include density, radiation intensity, field strength, directivity phase or polarization. A trace of the received electric (magnetic) field at a constant radius is called the amplitude field pattern.

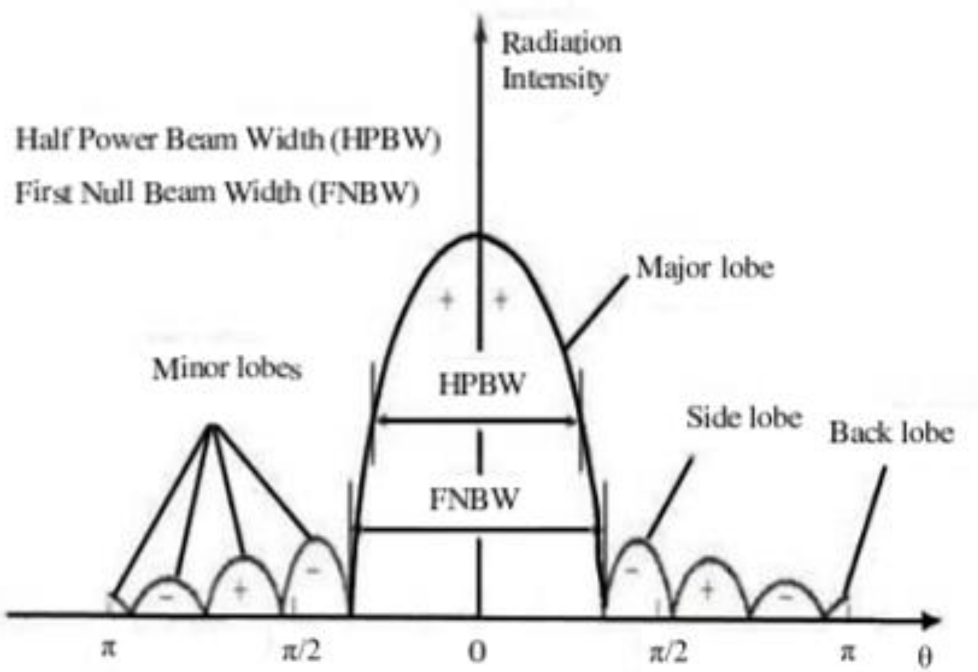
On the other hand, a graph of the spatial variation of the power density along a constant radius is called an amplitude power pattern. The field and power patterns are often normalized with respect to their maximum value, yielding normalized field and power patterns[7]. The power pattern is usually plotted on a logarithmic scale or more commonly in decibels (dB). For an antenna, the field pattern (in linear scale) typically represents a plot of the magnitude of the electric or magnetic field as a function of the angular space; the power pattern (in linear scale) typically represents a plot of the square of the magnitude of the electric or magnetic field as a function of the angular space. The power pattern in (dB) represents the magnitude of the electric or magnitude field, in decibels, as a function of the angular space.

Radiation patterns have different parts which are referred to as lobes as shown in Figure 2.2-a. They are major, minor, side and back lobes. A radiation lobe is a portion of the radiation pattern bounded by regions of relatively weak radiation intensity.

[7] C. A. Balanis, Antenna Theory : Analysis and Design, 3rd ed. New York: John Wiley and Sons, Hoboken, NJ, 2005.



(a)



(b)

Figure 2.2-a (a) Radiation lobes and beamwidths of an antenna pattern (b) Linear plot of power pattern and its associated lobes and beamwidths

2.2.2 Isotropic, Directional, and Omni-directional patterns

An isotropic radiator is a lossless antenna having equal radiation in all directions. The directive properties of actual antennas are expressed with a reference to isotropic antenna, although it is ideal and not physically realizable. A directional antenna is one having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others. When maximum directivity is significantly greater than that of a half-wave dipole, it is called directional antenna.

- Isotropic - A hypothetical lossless antenna having equal radiation in all directions. It is only applicable for an ideal antenna and is often taken as a reference for expressing the directivity properties of actual antennas.
- Directional - An antenna having the property of radiating or receiving electro-magnetic waves more effectively in some direction than in others. Maximum directivity of this antenna is significantly greater than that of a half wave dipole.
- Omni-directional - An antenna having an essentially non-directional pattern in a given plane and a directional pattern in any orthogonal plane.

2.2.3 Antenna Directivity, Gain and Radiation Efficiency

Directivity D is defined as the ratio of the radiation intensity U in a given direction from the antenna to the radiation intensity averaged over all direction. The average radiation intensity is equal to the total power radiated by the antenna (P_{rad}) divided by 4π. So the directivity can be calculated by:

$$D = \frac{U}{U0} = \frac{4\pi \mathrm{U}}{\mathrm{Prad}}$$

Antenna gain G is closely related to the directivity, but it takes into account the radiation efficiency e_{rad} of the antenna as well as its directional properties, as given by:

$$G = Erad.D$$

Radiation efficiency (e_{rad}) is determined by the ratio of the radiated power, P_{rad} to the input power at the terminals of the antenna, P_{in}

$$Erad = \frac{Prad}{Pin} = \frac{G}{D}$$

2.2.4 Radiation Intensity

It is defined as the power radiated from an antenna per unit solid angle. The radiation intensity is a far-field parameter, and it can be obtained by simply multiplying the radiation density by the square of the distance. It is given in the mathematical form as follows:

$$U = r^2 Wrad$$

Where U is the radiation intensity (W/unit solid angle) and W_{rad} is the radiation density (W/m^2).

2.2.5 Beam Width

The beam width of an antenna pattern is defined as the angular separation between two identical points on opposite sides of the pattern maximum. Two most widely used beam widths are the Half-Power Beam Width (HPBW) and the First-Null Beam Width (FNBW). HPBW is defined by IEEE as: “In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam” [1]. FNBW is defined as the angular separation between the first nulls of the pattern. The beam width of antenna is a very important figure of merit and it is often used with the side lobe level. When the beam width decreases, the side lobe increases and vice versa. Moreover, the beam width of the antenna is also used to describe the resolution capabilities of the antenna to distinguish between two adjacent radiating sources or radar targets. The most common resolution criterion states that the resolution capability of an antenna to distinguish between two sources is equal to half the First-Null Beam Width (FNBW/2)[8] which is usually used to approximate the HPBW[9].

2.2.6 Bandwidth

Bandwidth is the main characteristic of the wideband antenna. The bandwidth can be considered to be the range of frequencies, on either side of the centre frequency, where the antenna characteristics are within an acceptable value. The bandwidth can be described in terms of percentage of the centre frequency, f_C, of the band.

[8] J. D. Kraus, Radio Astronomy. New York: McGraw-Hill, 2002

[9] J. D. Kraus and R. J. Marhefka, Antennas. New York: McGraw-Hill, 2002.

$$BW = \frac{fH - fL}{fC} * 100 = 2\frac{fH - fL}{fH + fL} * 100$$

Where f_H is the highest frequency in the band and f_L is the lowest frequency in the band. The centre frequency can is calculated from

$$fc = \frac{fH + fL}{2}$$

For broadband antennas, the bandwidth can also be expressed as the ratio of the highest frequency to the lower frequency, where the antenna performance is acceptable. It is given by:

$$B = \frac{fH}{fL}$$

3. Wideband antenna & FEKO

Wideband antennas are an essential part of communication systems. Extensive research has been conducted on various types of antennas, ranging from simple wire antennas to planar antennas. However, it is necessary to select an antenna with a compact size and wideband characteristics for wideband applications. Some wideband antennas were examined such as Vivaldi antenna, sinuous antenna, and spiral antennas, which belong to frequency independent antennas, are selected in this project due to their planar structure, low profile, wide bandwidth characteristics, and circular polarization.

3.1 Frequency Independent Antennas

Frequency independent antennas[10] are antennas whose radiation pattern, impedance and polarization remain unchanged over a large bandwidth[11]. Frequency independent antennas exist in several configurations such as equiangular, sinuous and Archimedean[12]. Frequency independent antenna can be completely defined by angles. The general formula for their shape is given by the following equation and it was taken from[10].

$$e^{a(\varphi+\varphi 0)} F\ (\theta)$$

Where ρ, θ and ϕ are the usual spherical coordinates, a and ϕ0 are constants and F(θ) is any function of θ.

[10] V. H. Rumsey, “Frequency independent antennas,” IRE National Convention Record, vol. 5, pp. 114–118, 1957.
[11] K. Louertani, R. Guinvarc’h, N. Ribiere-Tharaud, and M. Darces, “Design of a spiral antenna with coplanar feeding solution,” Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE, pp. 1–4, 2008.
[12] Y. T. Lo, “A mathematical theory of antenna arrays with randomly spacedelements,” IEEE Transactions on Antennas and Propagation, vol. 12, pp. 257–268, 1964.

Frequency independent antennas provide uniform electrical characteristics over a wide frequency band. However, frequency independent antennas have broad radiation patterns and low gain in general, which is not suitable for some applications. This problem can be resolved by using an array of frequency independent antenna elements. The wideband characteristics of the frequency independent element are lost in the array environment even as the above method allows for pattern control and higher gains.

3.2 FEKO

FEKO[13] is a software Suite intended for the analysis of a wide range of electromagnetic problems. Applications include EMC analysis, antenna design, microstrip antennas and circuits, dielectric media, scattering analysis and many more. The kernel provides a comprehensive set of powerful computational methods and has been extended for the analysis of thin dielectric sheets, multiple homogeneous dielectric bodies and planar stratified media.

The Method of Moments (MoM) technique forms the basis of the FEKO solver. Other techniques such as the Multilevel Fast Multipole Method (MLFMM), the Finite Element Method (FEM) Uniform Theory of Diffractions (UTD), Geometrical optics (ray launching) and Physical Optics (PO) have been implemented to allow the solving of electrically large problems and inhomogeneous dielectric bodies of arbitrary shape.

3.2.1 Method of Moments

The core of the program FEKO is based on the Method of Moments (MoM). The MoM is a full wave solution of Maxwell's integral equations in the

[13] FEKO, Comprehensive Electromagnetic solutions, SA.

frequency domain. An advantage of the MoM is that it is a "source method" meaning that only the structure in question is discretised, not free space as with "field methods". Boundary conditions do not have to be set and memory requirements scale proportional to the geometry in question and the required solution frequency. The following special extensions have been included in FEKO's MoM formulation to enable the modeling of magnetic and dielectric media.

- Surface Equivalence Principle (SEP): The SEP introduces equivalent electric and magnetic currents on the surface of a closed dielectric body. The surface of such bodies can be arbitrarily shaped and is discretised using triangles.
- Volume Equivalence Principle (VEP): The VEP allows the creation of dielectric bodies from cuboids. More basis functions are typically required than for the SEP, but neighboring cuboids may have differing electric and magnetic properties.
- Planar Green's Functions for Multilayered Media: Multilayered dielectric media may be modelled with Greens functions, e.g. substrates for microstrip architecture. The special Greens function formulation implements 2D infinite planes with finite thickness to handle each layer of the dielectric. Conducting surfaces and wires inside the dielectric layers have to be discretised, but not the dielectric layers themselves. Metallic surfaces and wires can be arbitrarily oriented in the media and are allowed to cross multiple layers. (Calculations using Greens functions are accelerated by using interpolation tables.)
- Thin Dielectric Sheets: Multiple layers of thin dielectric and anisotropic sheets can be analyzed as a single layer in FEKO. Typical applications

are the analysis of radome covered antennas and windscreens of automobiles.

3.2.2 Multilevel Fast Multipole Method (MLFMM)

The MLFMM is an alternative formulation of the technology behind the MoM and is applicable to much larger structures than the MoM, making full-wave current-based solutions of electrically large structures a possibility. This fact implies that it can be applied to most large models that were previously treated with the MoM without having to change the mesh.

The agreement between the MoM and MLFMM is that basis functions model the interaction between all triangles. The MLFMM differs from the MoM in that it groups basis functions and computes the interaction between groups of basis functions, rather than between individual basis functions. FEKO employs a boxing algorithm that encloses the entire computational space in a single box at the highest level, dividing this box in three dimensions into a maximum of eight child cubes and repeating the process iteratively until the side length of each child cube is approximately a quarter wavelength at the lowest level. Only populated cubes are stored at each level, forming an efficient tree-like data structure. In the MoM framework the MLFMM is implemented through a process of aggregation, translation and disaggregation of the different levels. The MoM treats each of N basis functions in isolation, thus resulting in an N2 scaling of memory requirements (to store the impedance matrix) and N3 in CPU-time (to solve the linear set of equations). It is thus clear that processing requirements for MoM solutions scale rapidly with increasing problem size. The MLFMM formulation's more efficient treatment of the same problem results in N∗log(N) scaling in memory and N∗[log(N)]2 in CPU time. In real applications this reduction in solution requirements can range to orders of magnitude.

Significant effort has also been invested in improving the parallel MLFMM formulation to achieve exceptionally high efficiency when distributing a simulation over multiple processors.

3.2.3 Finite Element Method (FEM)

The FEM is applicable to the modelling of electrically large or inhomogeneous dielectric bodies, which are not efficiently solvable with FEKO's extensions to the MoM. The FEM is a volume meshing technique that employs tetrahedral to accurately mesh arbitrarily shaped volumes where the dielectric properties may vary between neighboring tetrahedral. FEM modelling is advantages in these instances because FEM solution matrices are sparse, where MoM matrices are densely populated, making FEM matrices significantly better scalable with an increase in frequency.

4. Vivaldi Antenna

4.1 Introduction

The Vivaldi antenna is a member of class of aperiodic continuously scaled traveling wave antenna structures. Wide-Band technology requires antennas with broad bandwidth and minimum distortion of received and radiated signals. Moreover, wide-band airborne applications have strict requirements on the size of antenna arrays to be used due to the limited space. The tapered slot antennas (TSA) are the best candidates for use in wide band applications. These antennas offer a wide bandwidth, significant gain and symmetric patterns in both co-polarization and cross-polarization. TSAs are efficient and light weight. In addition, TSAs are appreciably simple in geometry making them more advantageous. The most commonly used class of TSA in wide band technology is Vivaldi antenna.

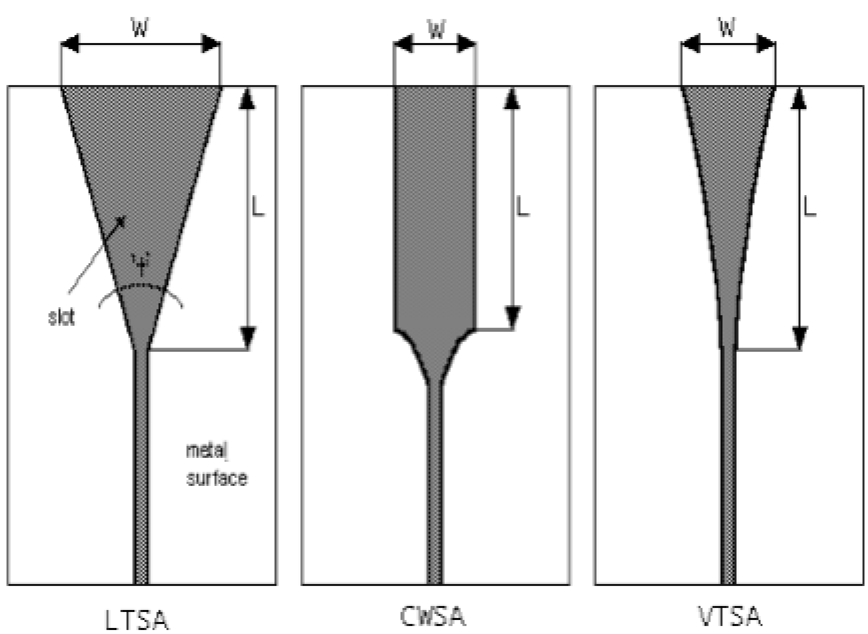


Figure 4.1-0-a Basic types of Vivaldi antenna

Vivaldi antenna, first introduced by Gibson[14] in 1979, has an exponentially tapered slotline. As a member of the class of TSA, Vivaldi antenna provides broad bandwidth, low cross polarization and directive propagation at microwave frequencies. Vivaldi antennas are low cost, easy to fabricate and fairly insensitive to dimensional tolerances in fabrication process due to printed circuit technology used for the construction of these antennas. It shall be also noted that the beamwidth and directivity of a Vivaldi antenna might be considerably improved varying the design parameters.

In this work, it is aimed to investigate Vivaldi antenna design parameters regarding their effects on antenna impedance, return loss response, and reverse gain characteristics.

4.2 Prior Art

Lewis et al.[15] introduced tapered slot antenna as a broadband stripline array element capable of multioctave bandwidths in his study in 1974. Following TSA, Vivaldi antenna, an exponentially tapered slot antenna, was originated by Gibson[14] in 1979. Gibson stated that Vivaldi antenna had significant gain and linear polarization in a frequency range from below 2 GHz to above 40 GHz. Gibson's Vivaldi antenna with an asymmetric one sided microstrip to slotline transition was constructed on alumina using microwave photolithographic thin film techniques. It served fairly well as an 8-40 GHz video receiver module.

[14] P. J. Gibson, "The Vivaldi Aerial," Proc. 9th European Microwave Conference, Brighton, U.K., Oct. 1979, pp. 101-105.

[15] L. R. Lewis, M. Fasset, and J. Hunt. "A broadband stripline array," IEEE A P-S Synip., June 1974, p. 335.

E. Gazit[16] proposed two important changes to the traditional Vivaldi design. He used a low dielectric substrate (cuclad, ϵ=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.

Schuppert[17] came up with circular stubs applied to microstrip to slotline transitions in order to offer an easier fabrication whereas Sloan et al.[18] used radial stubs instead of circular ones and improved the bandwidth of these kinds of transitions. Schaubert[19] used both circular and radial stubs in order to design a stripline-fed, metal fins placed on both sides of the element, Vivaldi antenna. He stated in his study that the bandwidth of the antenna was improved with these nonuniform 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.

4.3 The Principle of Operation

The Vivaldi antenna, having an exponentially tapered slot profile, is a type of tapered slot antenna (TSA). The Vivaldi antenna belongs to the surface wave class of traveling wave antennas (the other traveling wave antenna type is the leaky wave antenna). In order to describe principle of operation, the

[16] E. Gazit, "Improved design of a Vivaldi antenna," IEEE Proc. H, April 1988, pp. 89-92.
[17] B. Schuppert, "Microstrip/Slotline Transitions: Modeling and Experimental Investigation," IEEE Transactions on Microwave Theory and Techniques, Vol. 36, No. 8, August 1988, pp. 1272-1282.
[18] R. Sloan, M. M. Zinieris, L. E. Davis, "A broadband microstrip to slotline transition," Microwave and Optical Technology Letters, Vol. 18, No. 5, August 1998, pp. 339-342.
[19] D. H. Schaubert, J. Shin, "A Parameter Study of Stripline-Fed Vivaldi Notch Antenna Arrays," IEEE Transactions on Antennas and Propagation, Vol. 47, No. 5, May 1999, pp. 879-886.

surface wave antennas can be divided into two sections: propagating section and radiating section. The slot width (separation between the conductors) is smaller than one-half free space wavelength ($\lambda_0/2$) and the waves traveling down the curved path along the antenna are tightly bound to the conductors in the propagating section. The bond becomes progressively weaker and the energy gets radiated away from the antenna coupling to the air in the radiating section where the slot width is increasing beyond the one-half wavelength. The waves are traveling along the antenna surface until the limiting case of phase velocity is equal to the free space velocity of light ($c=3x10^8$). The limiting case intends the antenna with air.

4.4 Design and Simulation

Design of Vivaldi antennas rely on various parameters such as exponential taper, taper rate, taper width, length and width of metal patch etc. Taper of Vivaldi antenna is designed based on the following equation.

$$Y = c1.e^{Rx} + c2$$

Where,

$$\mathrm{C1} = \frac{\mathrm{y2} - \mathrm{y1}}{\mathrm{eRx2} \ - \mathrm{eRx1}}$$

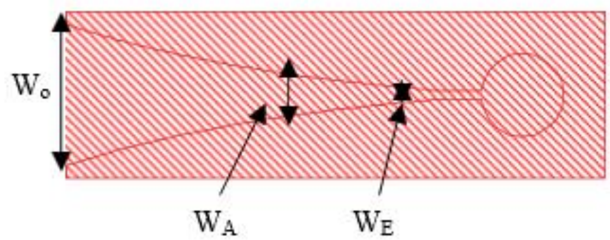
$$\mathrm{C1} = \frac{\mathrm{y1eRx2} \ - \mathrm{y2eRx1}}{\mathrm{eRx2} \ - \mathrm{eRx1}}$$

The top and bottom layers show the exponential taper profile[20] which is defined by the opening rate R and the two points P1 (x1,y1) and P2 (x2,y2) (use the first and the last points of the exponential taper).

[20] Greenberg, M. C., L. Virga, and C. L. Hammond, "Performance characteristics of the dual exponentially tapered slot antenna for wireless communication application," IEEE Trans. on Vehicular Technology, Vol. 52, 305–310, Mar. 2003.

Given the highest frequency of operation (fH), the width W of the Vivaldi antenna should satisfy following equation[21] to operate on wide band of frequency as shown in figure below.

$$w0 < \frac{c}{fH\sqrt{\varepsilon r}}$$



W$_E$ - Input slot width

W$_A$ - Slot width at radiating area

W$_O$ - Output slot width

Figure 4.4-a Demonstration of Vivaldi taper parameter

Antenna length should be greater than a free space wavelength at the lowest frequency of operation. The lowest frequency of operation, thus the bandwidth, is also dependent on the antenna length; increasing antenna length provides a wider bandwidth. However, when the requirements on the gain and beamwidth are not so strict, an antenna length on the order of the lamda$_0$ will also be enough to get the desired bandwidth.

Antenna width shall be greater than one-half wavelength at the lowest frequency of operation, lamda/2, so as to accomplish the desired radiation performance. Decreasing antenna width below this value decreases the lowest frequency of operation, thus the antenna bandwidth considerably.

Choosing a substrate material of appropriate dielectric constant and tangent loss shall be the first design step. Dielectric constant and the substrate

[21] Antenna Engineering Handbook,Ch.24, Ultra wideband Arrays by J.J. Lee, Raytheon space and Airborne systems, McGraw-Hil.

thickness determine the phase velocity of the waves. Propagation of the waves along the antenna lasts until the limiting case of phase velocity is equal to the free space velocity of light. Thus, the waves will merely radiate in an antenna with air as dielectric.

Dielectric constant and **substrate thickness** are the parameters determining the performance and radiation pattern, which is beamwidth, sidelobe level and gain of the antenna. Higher dielectric constant substrates give the advantage of smaller antenna dimensions for same performance. However, a more efficient design and a wider bandwidth is possible with low dielectric constant substrates. Low dielectric constant substrates also lower the scattering along the antenna and consequently spurious fields. Thus, the second parameter, tangent loss, shall also be considered to cope with this trade-off. Among the substrates with dielectric constant in the range of 2.2 to 10.2, Rogers RT/duroid™ 5880 has the minimum tangent loss (tan = 0.0009) and a dielectric constant of $\epsilon r = 2.2$. Rogers RT/duroid™ 5880 is chosen as the substrate material to be used in this work.

Substrate thickness is restricted to the standard thickness values given by the laminate productor. An improvement in the performance is obtained using thicker substrates due to a decrease in the antenna reactance through the whole band. Besides, thicker substrate results in higher antenna gain narrowing the main beam and increasing the sidelobes. However, increasing the substrate thickness generates deeper nulls in the return loss curve. Any change (increase/decrease in substrate thickness) does not affect the bandwidth considerably.

Matlab code is written as in Appendix A to generate taper exponential curve. Points from resulting exponential curve are exported to Feko to design the radiating metal patch of Vivaldi. Impedance matching with the input port is obtained by calculating impedance as given in the following equation. Matlab code is written from equation to obtained the balanced substrate thickness such that to maintain the width and height of antenna.

Characteristic dimension of antenna are given below:

Feature	Description/Value
Material	Rogers RT/duroid™ 5880, 2mm thick , ϵr=2.2
Antenna length	90mm
Antenna width	50mm
Aperture height	30
Taper rate	0.18

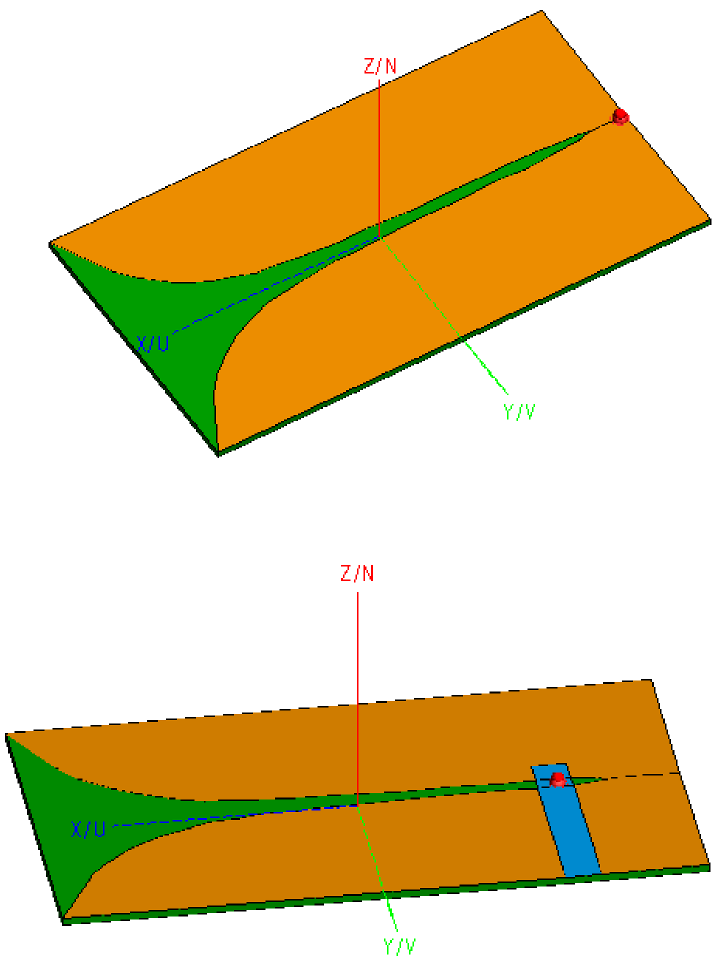
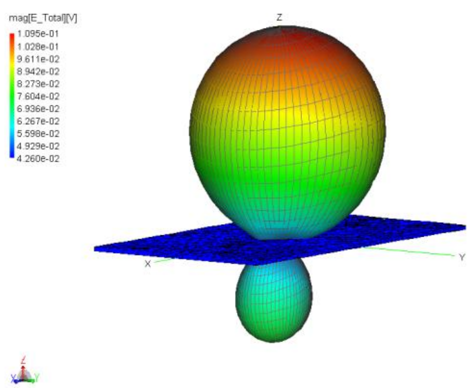
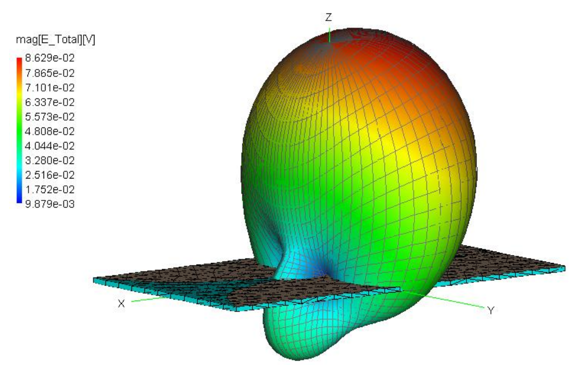


Figure 4.4-b 3-D view of model designed in Feko.

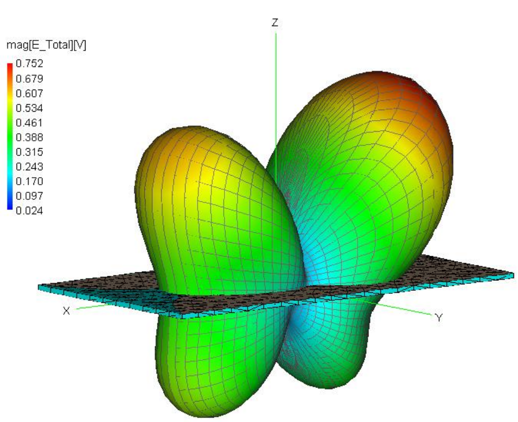
4.5 Results and Discussion



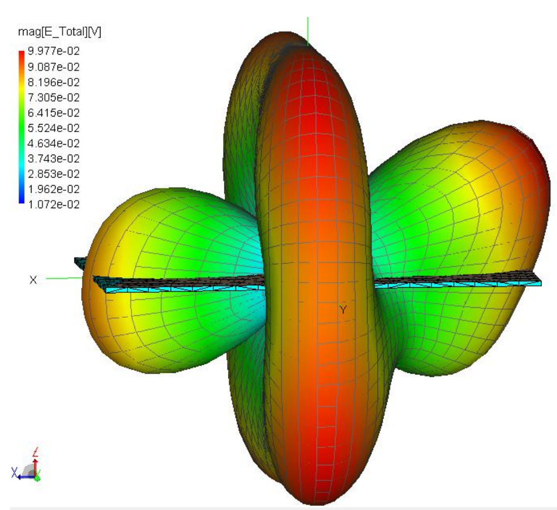
(a)



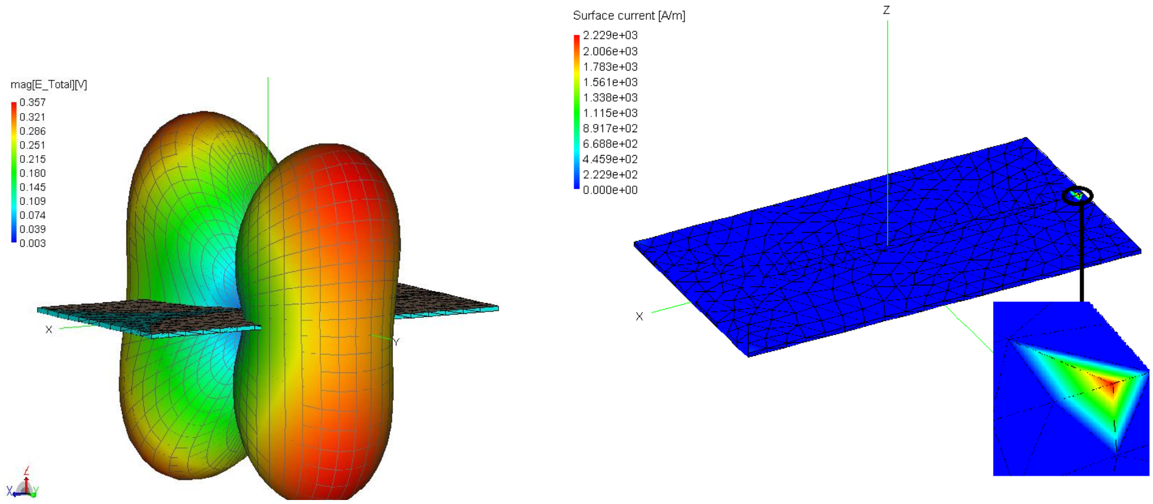
(b)



(c)



(d)



(e) (f)

Figure 4.5-a 3-D Radiation Pattern for (a) 1GHz (b) 1.75 GHz (c) 2.5 GHz (d) 3.25 GHz (e) 4 GHz (f) Current distribution on Vivaldi antenna

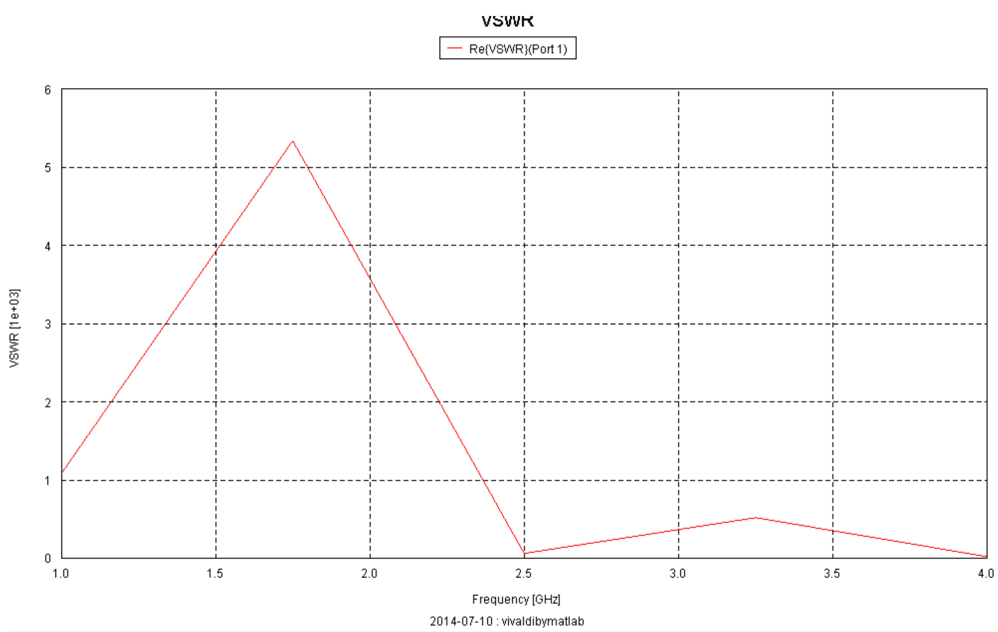
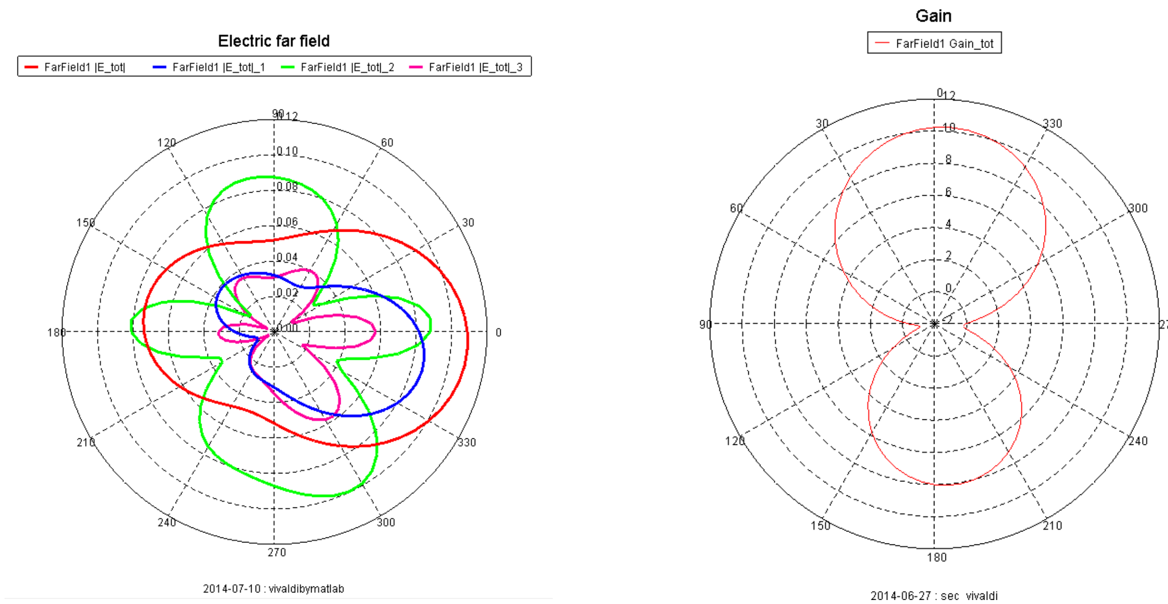


Figure 4.5-b VSWR Plot



(a) (b)

Figure 4.5-c (a) 2-D Far field at different frequency (b) Gain at 1 GHz

This antenna is showing remarkable performance over the entire frequency range between 2.5 GHz–4GHz with high gain up to more than 10dB and very low Cross polarization. This antenna can be used as an element in phased arrays for wide band wide angle scanning because of its wide beam width in both the planes and also providing wide bandwidth. This antenna has a narrow beam in front of the antenna and can be used for broadband scanning. Standing wave ratio of the antenna is good at 1 GHz and increased till 2.5 GHz after that again VSWR is proper as requirement for the designed antenna .This may be because of impedance mismatching of the structure and the input.

5. Sinuous Antenna

5.1 Introduction

The sinuous antenna was originally conceived by DuHamel in 1982[22]. This particular antenna is broadband and capable achieving dual orthogonal linear[23] or circular polarizations from the same aperture. These antennas are based on the following equation:

$$\varphi(r) = (-1)^p.\alpha_p.\sin\left[(\pi.\ln\left(\frac{r}{R_p}\right))/(T_p)\right]$$

Where ϕ is the angular position, r is the radial position, τ is the growth rate, α is the angular arm width, p is the cell number, and Rp is the radius of the p_{th} cell. The growth rate can either be constant of vary logarithmically with radius. Design equation in spherical co-ordinate[24] is given by following equation:

$$R(t) = -Rp * growth_{rate}^{ceil\left(\frac{t}{Ni}\right)-1} * (1 - growth_{rate}) * \frac{\left(t - Ni * \left(ceil\left(\frac{t}{Ni}\right)\ - 1\right)\right)}{Ni} + Rp * growth_{rate}^{ceil\left(\frac{t}{Ni}\right)-1}$$

[22] R. H. DuHamel, "Dual Polarized Sinuous Antennas," U.S. Patent 4658262, April 14, 1987.

[23] M. C. Buck and D.S. Filipović, "Split-Beam Mode Four-Arm Slot Sinuous Antenna," Antennas and Wireless Propagation Letters, Volume 3, Issue 1, 2004 Page(s): 83 - 86.

[24] R. C. Johnson, Antenna Engineering Handbook, Chapter 14, pp. 14-1 - 14-68, Third. Edition, McGraw-Hill, 1993.

$$\emptyset(t) = \left((-1)^{\mathrm{ceil}\left(\frac{\mathrm{t}}{\mathrm{Ni}}\right)}\right) * \mathrm{angular}_{\mathrm{width}} * \sin((\mathrm{pi} * \ln((-\mathrm{Rp} * \mathrm{growth}_{\mathrm{rate}}^{\left(\mathrm{ceil}\left(\frac{\mathrm{t}}{\mathrm{Ni}}\right)-1\right)} * (1 - \mathrm{growth\_rate}) * \frac{\mathrm{t} - \mathrm{Ni} * \left(\mathrm{ceil}\left(\frac{\mathrm{t}}{\mathrm{Ni}}\right) - 1\right)}{\mathrm{Ni}} + \mathrm{Rp} * \mathrm{growth}_{\mathrm{rate}}^{\mathrm{ceil}\left(\frac{\mathrm{t}}{\mathrm{Ni}}\right)-1}) / (\mathrm{Rp} * \mathrm{growth}_{\mathrm{rate}}^{\mathrm{ceil}\left(\frac{\mathrm{t}}{\mathrm{Ni}}\right)-1}))) / \ln(\mathrm{growth\_rate}))$$

$$\theta(t) = 90$$

The planar sinuous antenna is a bi-directional structure, radiating in both half- spaces. If one desires unidirectional operation from this planar structure, an absorptive material must be placed on one side of the aperture and is typically enclosed in a cavity.

5.2 Prior Art

Recent research has shown that sinuous antennas can operate in a multiband and multipolarized manner[25] [26] [27] instead of the typical broadband mode. Sinuous antennas, in their typical broadband operation, can support (N-1)/2 modes, where N is the number of arms the structure has.[28] Frequency independence of the input impedance is highly desirable property of any antenna element, because it makes it easier to efficiently couple the RF energy to the radiating element at all frequencies, without the

[25] M. C. Buck, A. Bhobe, and D.S. Filipović, "A Flush-Mounted Multi- Band/Broadband Sinuous-Like Slot Antenna for Terrestrial Communications," URSI National Radio Science Meeting, June 2003.

[26] M. C. Buck and D.S. Filipović, "Split-Beam Mode Four-Arm Slot Sinuous Antenna," Antennas and Wireless Propagation Letters, Volume 3, Issue 1, 2004 Page(s): 83 - 86.

[27] M. C. Buck, J. Burford, and D.S. Filipović, "Multiband Two Arm Slot Sinuous Antenna," IEEE Antennas and Propagation Society Symposium Proceedings, Volume 1, 20-25 June 2004 Page(s): 165 – 168.

[28] Kamaljeet Singh Saini and Richard F. Bradley , "The Sinuous Antenna A dual polarized element for wideband phased array feed application", February 13, 1996

need to resort to frequency dependent impedance transforming networks. It was shown by Booker[29].

5.3 Design and Simulation

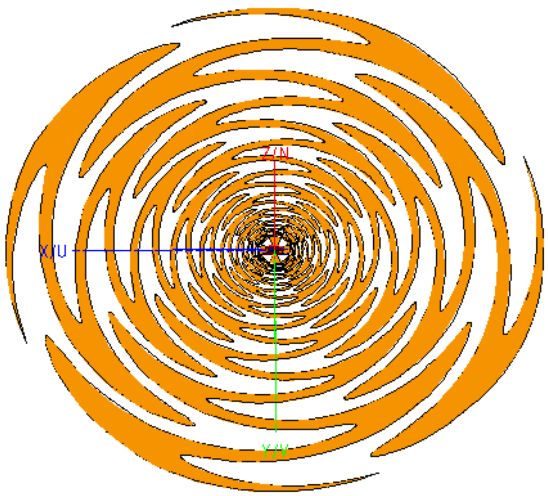
Design of sinuous antenna involves generation of sinuous curve and creation of sinuous pattern using aforementioned equation[30]. The requirement of dual polarization dictates the need to have two equivalent structures, each catering to one sense of polarization. This is done by first generating one set of "arms" to achieve a linear polarization, and then adding another set of arms, similar to the first one, but rotated through 90^0 , to provide the orthogonal polarization sense. It has to be ensured that the two sets of "arms" do not intersect each other, and the geometry of the structure confirms to the log periodic principles, and is self complimentary as well. Sinuous curve is generated using given equation[30] . The sinuous curve obtained above was swept through an angle ±δ about its axis to generate one sinuous arm. This arm was then copied after rotation 90^0 about the origin.

A sinuous structure was generated as outlined above with the following design parameters: α = 45°, T = 0.75. A self complimentary structure was ensured by setting $\delta = 22.5^0$. As shown by Booker, an N-arm, self complimentary structure has a balanced input impedance of each arm pair given by:

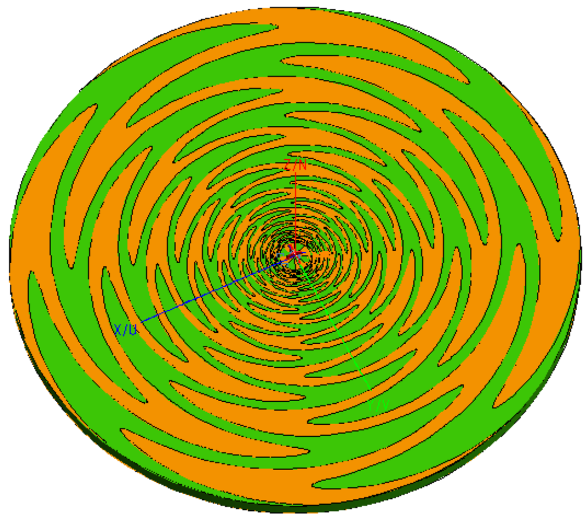
$$Z_m = \frac{60\pi}{\sin\frac{M\pi}{N}}$$

[29] H . G. Booker: "Slot. Aerials and Their Relation to Complimentary Wire Aerials (Babinet's Principle)." JJEE(London), pt.IIIA. pp.620-627, 1946.
[30] R. H. DuHamel, "Dual Polarized Sinuous Antennas," U.S. Patent 4658262, April 14, 1987.

Where M is the mode number, when fed in mode-1, a four arm structure will therefore present an input impedance of 267 Ω. The actual impedance is somewhat lower owing to the feed structure at the center. Overview of model designed in Feko.



(a)



(b)

Figure 5.3-a (a) sinuous antenna on air (b) Cavity backed sinuous antenna

5.4 Results and Discussion

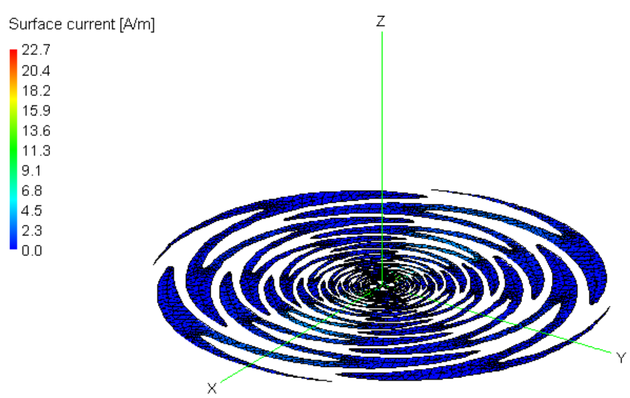


Figure 5.4-a Current distribution in sinuous structure

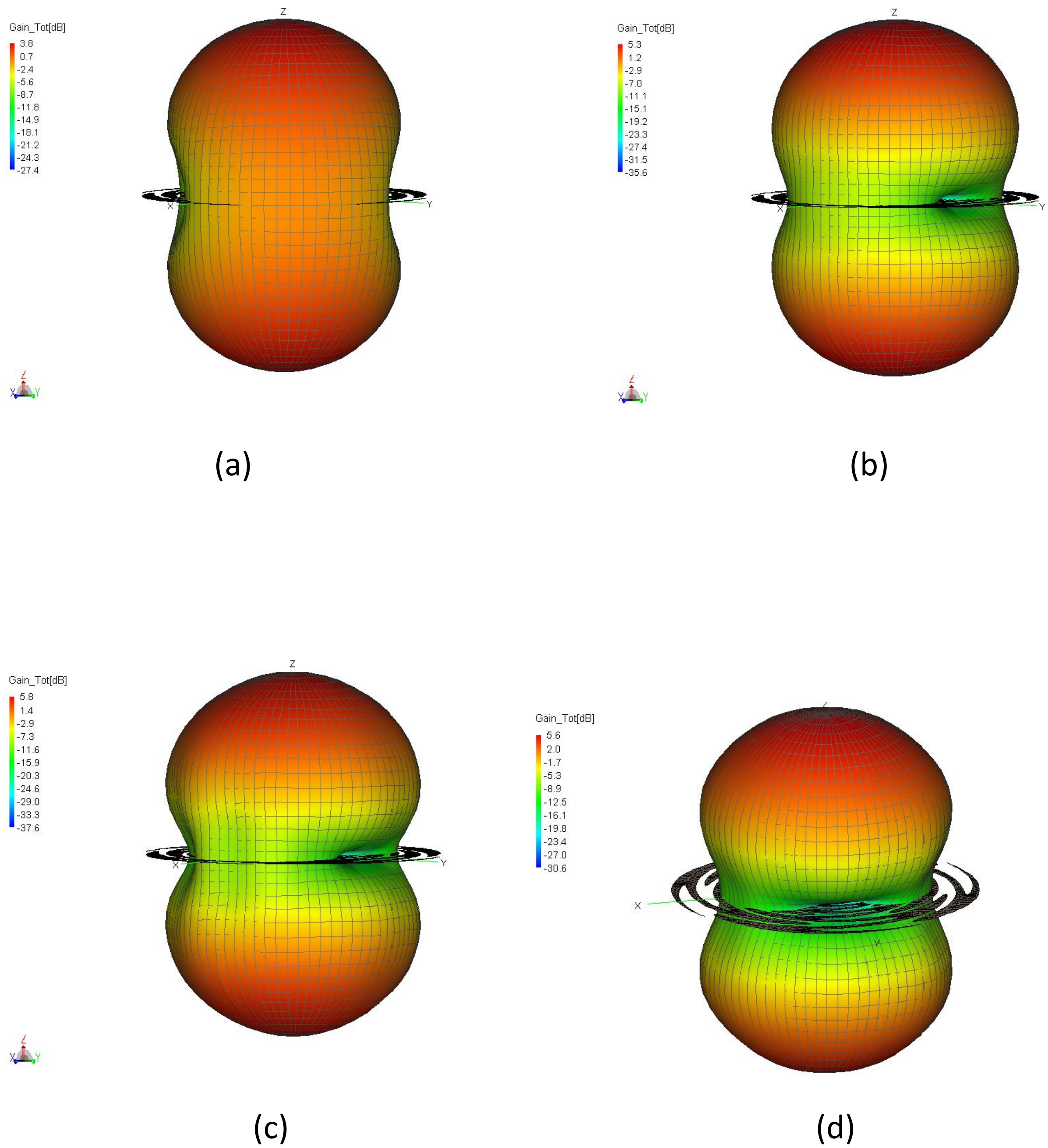
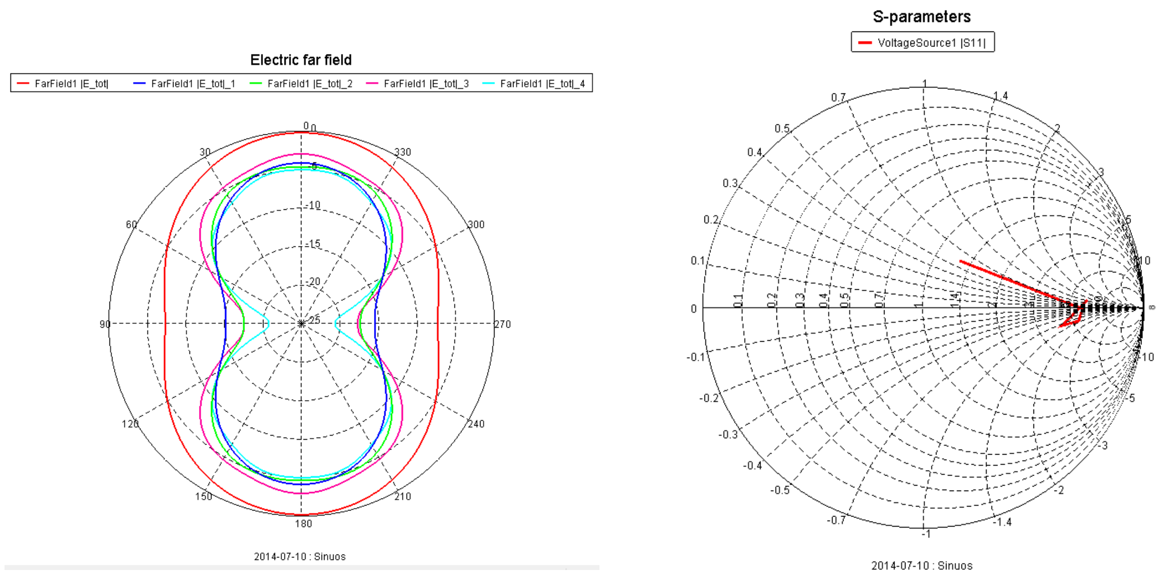


Figure 5.4-b 3-D Radiation Pattern (a) 300MHz (b) 1.96GHz (c) 2.7GHz (d) 3.6GHz



(a) (b)

Figure 5.4-c (a) Radiation pattern 2-D plot (b) Smith chart S-parameter

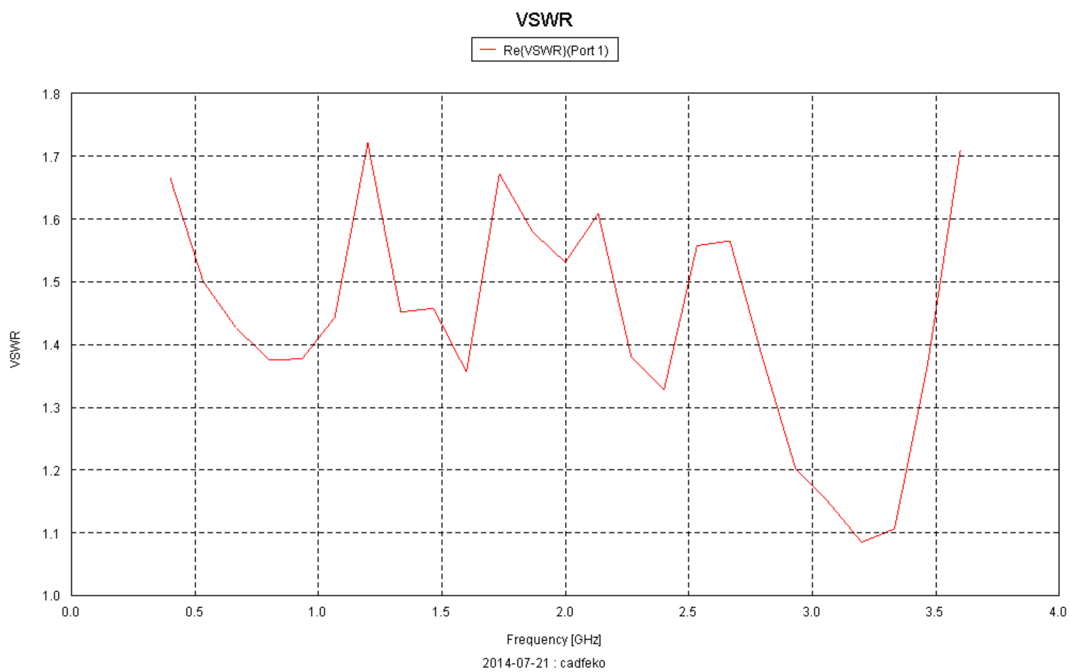


Figure 5.4-d VSWR Plot

Radiation of sinuous is on both sides of the antenna plane. So, cavity with absorber is added as shown in Fig 5.3-a (b). Simulation results of cavity backed sinuous antenna are as:

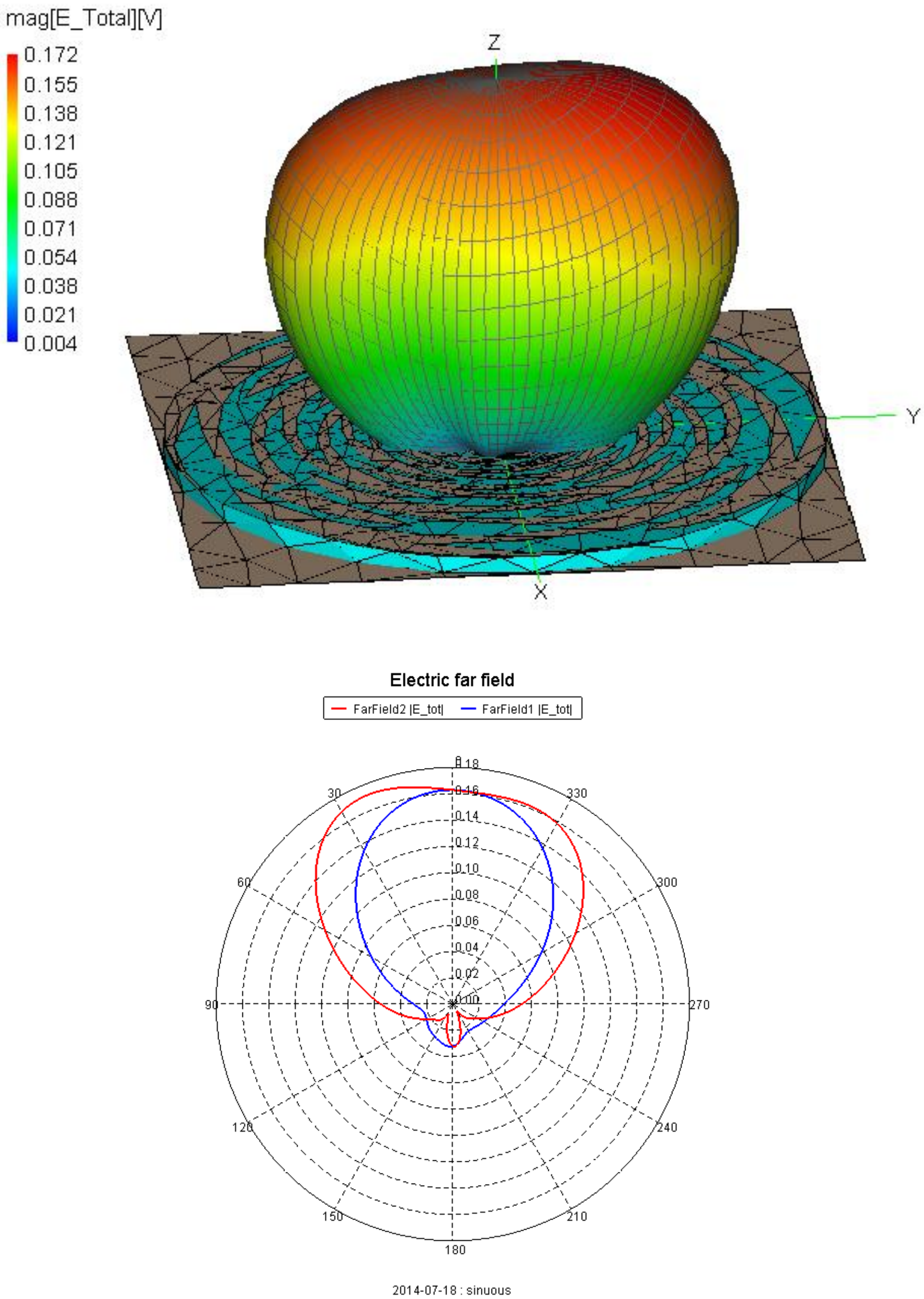


Figure 5.4-e (a) 3-D Radiation pattern (b) 2-D plot of radiation pattern of cavity backed sinuous antenna

6. Multi-arm Spiral Antenna

6.1 Introduction

Spiral antenna is one of the wideband antennas which has multiple inputs and can be operated to achieve wide band application. A Spiral antenna is well known to be suitable for many applications requiring a large bandwidth, circular polarization (RHCP and LHCP) like WLAN communications, Differential global Positioning system (DGPS) ground station.

The first very wide-band antenna using spiral topology was invented by Ed Turner in 1950s. Rumsey advanced the equiangular spiral theory in 1954 and then, Burdine and Jones, et al. helped explain its performance in 1960s[31].

The spiral antenna can be left-hand or right-hand circularly polarized. The advantage of the spiral antenna is that it has a very wide band but its weakness is that it has a very low gain. The spiral antenna can be excited by driving opposite arms with equal amplitude and different phases. The most popular design is based on the Archimedean Spiral Equation such as:

$$r1(\phi) = (d+w)\,\phi/360^\circ + r_a \qquad \phi_i < \phi < \phi_e$$

$$r2(\phi) = (d+w)(\phi - 180^\circ)/360^\circ + r_a \qquad \phi_i + 180^\circ < \phi < \phi_e + 180^\circ$$

Where, r1 (ϕ) is the radial distance from the origin to the arbitrary point on the centerline of the spiral, r1 (ϕ) the winding angle, and d the radial distance between initial point and ending points after one turn. r_a is the radial distance from the origin to the initial point of the spiral line, with w

[31] Joseph A. Mosko, ’An Introduction to Wideband, Two-Channel Direction-Finding Systems I, II, ’ Microwave Journal, February 1984

the line width designed as 50 Ω[32]. In most cases, the spiral antenna is fed at the center with single source. However, it is possible to have four feed with different phase to be at the center of the antenna. A 3-arm spiral antenna with co-planar feeding solution has been proposed by J.D Muller et. al[33] and a 2- arm with outer feed is proposed by EGschwendtner et.al.

In most cases, a spiral antenna consists of a thin metal foil spiral pattern etched on a substrate fed from the centre. Spiral antennas radiate bi-directionally. However, most of the applications require unidirectional radiation characteristics as well as having low profile. It can be resolved by adding a lossy cavity to the spiral antenna, backed by conductor, or adding absorbing materials. It absorbs the back radiation from the spiral providing for a wide bandwidth by reducing the reflection from ground plane.

6.2 Prior Art

Most of the previous research on spiral antennas was based on experiment and the band theory. Band theory is defined by the spiral antenna operating in the region where the circumference of the spiral is equal to a wavelength.

The lossy cavity improves the low frequency impedance behaviour and axial ratio of the spiral by reducing reflections from the end of the each arm of the spiral. Further-more, [34]showed that in order to reduce the reflected currents from the arm ends of the unbalanced-mode Archimedean spiral antenna, a ring-shaped absorbent material may be applied to the cavity. It

[32] Daeyoung Oh, Myungki Kim & Ikmo Park, 'Two-Arm Microstrip Spiral Antenna With A Circular Aperture On The Ground Plane ,' Microwave Communication Laboratory, Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea

[33] J.D. Muller and K. Sarabandi, Design and Analysis of a 3-arm spiral Antenna, IEEE Trans. Antennas Propagation, Vol 55, PP.258-266, Feb.2007.

[34] D. G. Shively and W. L. Stutzman, "Wideband arrays with variable element sizes,"Microwaves, Antennas and Propagation, IEE Proceedings H, vol. 137, no. 4, pp.238–240, August 1990.

also absorbs the back radiation from the spiral giving a large pattern bandwidth by reducing the reflection from the ground plane that causes pattern nulls[35],[36] . Reference [37], [38]and [39] showed that the conductor backed spiral antenna, where a metal ground plane is used as a conductor, has a 1:2:1 circular polarization bandwidth and to reflect unwanted power in order to get unidirectional path. However, in conductor backed spiral antenna, the conductors will reflect the radiated fields that enter the cavity. The author in [40] & [41] conducted experiments and obtained almost a constant input impedance and circular polarization over a wide beamwidth for a broad range of frequencies (2 to 18 GHz) by winding a long straight wire dipole into an Archimedean spiral shape.

[35] W. L. Stuzman, "Wide bandwidth antenna array design," Proceeding of the IEEE Southeastern Regional Meeting, Raleigh,NC, pp. 92–96, 1985.

[36] J. Thaysen, K. B. Jakobsen, and H. R. Lenler Eriksen, "Wideband cavity backed spiral antenna for stepped frequency ground penetrating radar," vol. 1B, 2005, pp. 418–421.

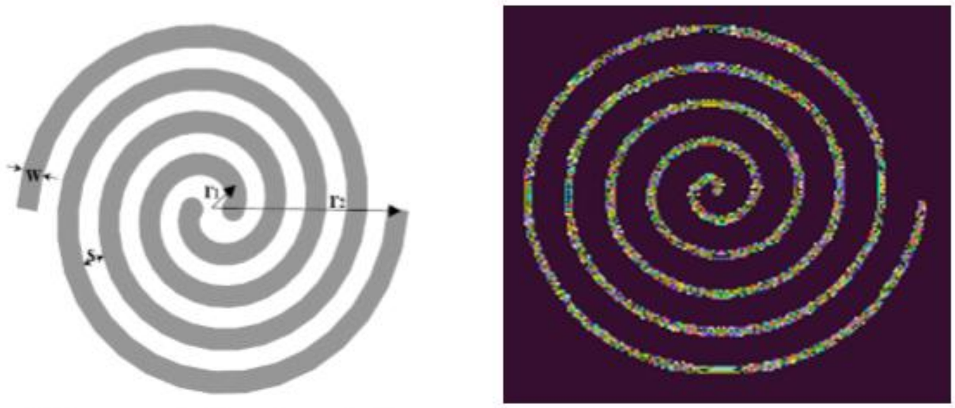
[37] H. Nakano, K. Nogami, S. Arai, H. Mimaki, and J. Yamauchi, "A spiral antenna backed by a conducting plane reflector," Antennas and Propagation, IEEE Transactions on, vol. 34, no. 6, pp. 791–796, 1986.

[38] W. Z. Wu, T. H. Chang, and J. F. Kiang, "Broadband slot spiral antenna with external feed and microstrip to slotline transition," Antennas and Propagation Society International Symposium, 2004. IEEE, vol. 1, pp. 767–770, June 2004.

[39] B. Wang and A. Chen, "Design of an Archimedean spiral antenna," 8th International Symposium on Antennas Propagation and EM Theory 2008 ISAPE 2008, pp. 348–351, 2008.

[40] J. H. Wang and V. K. Tripp, "Design and simulation of a planar archimedean spiral antenna," IEEE trans on antennas and propagation, vol. 39, no. 3, March 1991.

[41] H. Nakano, T. Igarashi, H. Oyanagi, Y. Iitsuka, and J. Yamauchi, "Unbalanced-Mode Spiral Antenna Backed by an Extremely Shallow Cavity," Antennas and Propagation, IEEE Transactions on, vol. 57, no. 6, pp. 1625–1633, 2009.



(a) Two-arm Archimedean spiral (b) Single-arm Archimedean spiral

Figure 2.12: Archimedean spiral antenna structure

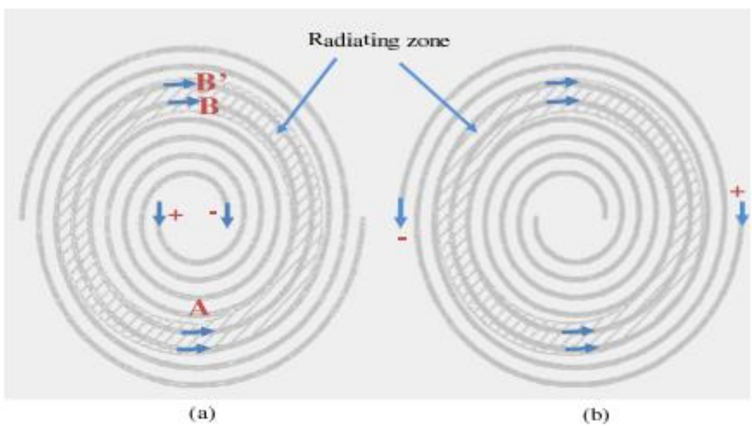


Figure 6.2-a Current vectors and radiating zone on two-arm spiral antenna with (a) Feeding in the center and (b) Feeding from outside

6.3 Design and simulations

The size of the antenna is computed from the lowest and the highest frequency of the operating frequency range. The low frequency operating point of the spiral is determined theoretically by the outer radius r2 and is given by:

$$fL = \frac{C_0}{2\pi r2\sqrt{\in \text{eff}}}$$

The high frequency operating point is based on the inner radius r1, giving:

$$fH = \frac{C_0}{2\pi r1\sqrt{\in \text{eff}}}$$

Where c0 is the propagation velocity in free space and ∈eff is the effective relative dielectric constant.

Antenna is designed to operate over the frequency range of 2 GHz to 6 GHz. Growth factor is taken as 0.24 and radius are evaluated using given equation above. Antenna is designed in Editfeko using the code given in appendix-2. In cadfeko, antenna parameters are calculated using the equation given above and model is designed.

Resulting design in Feko:

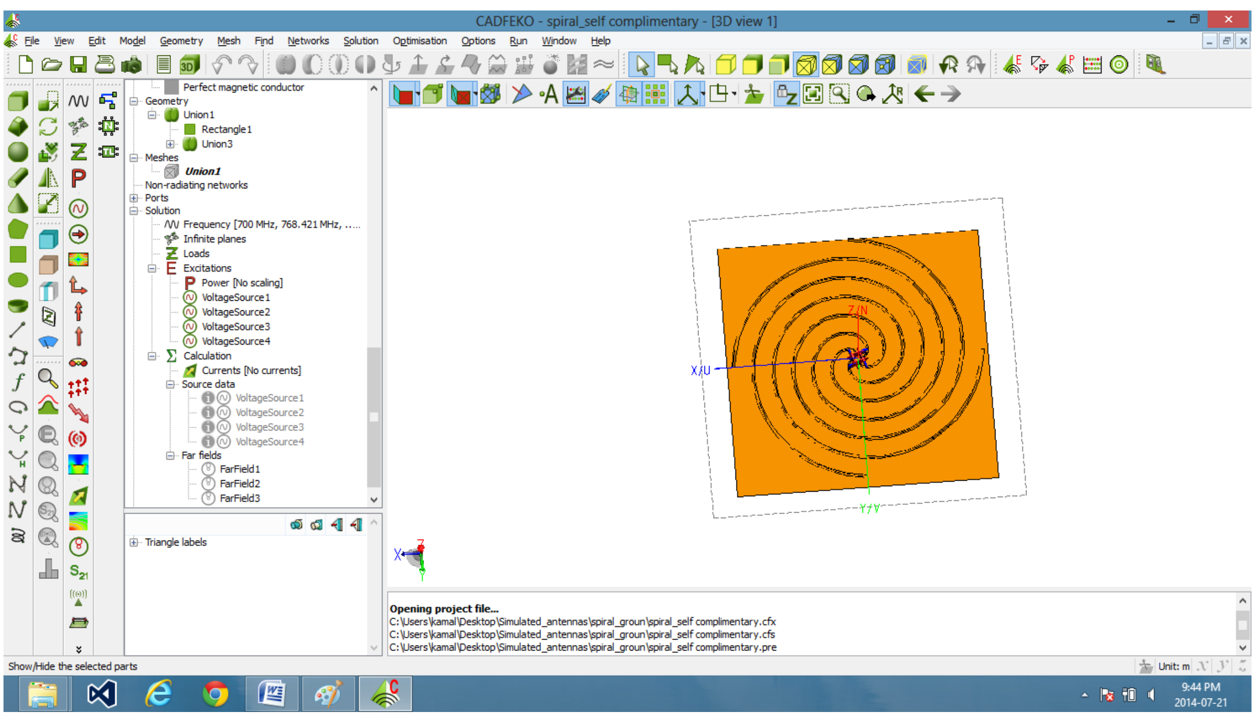


Figure 6.3-a Designed spiral antenna model in Cadfeko

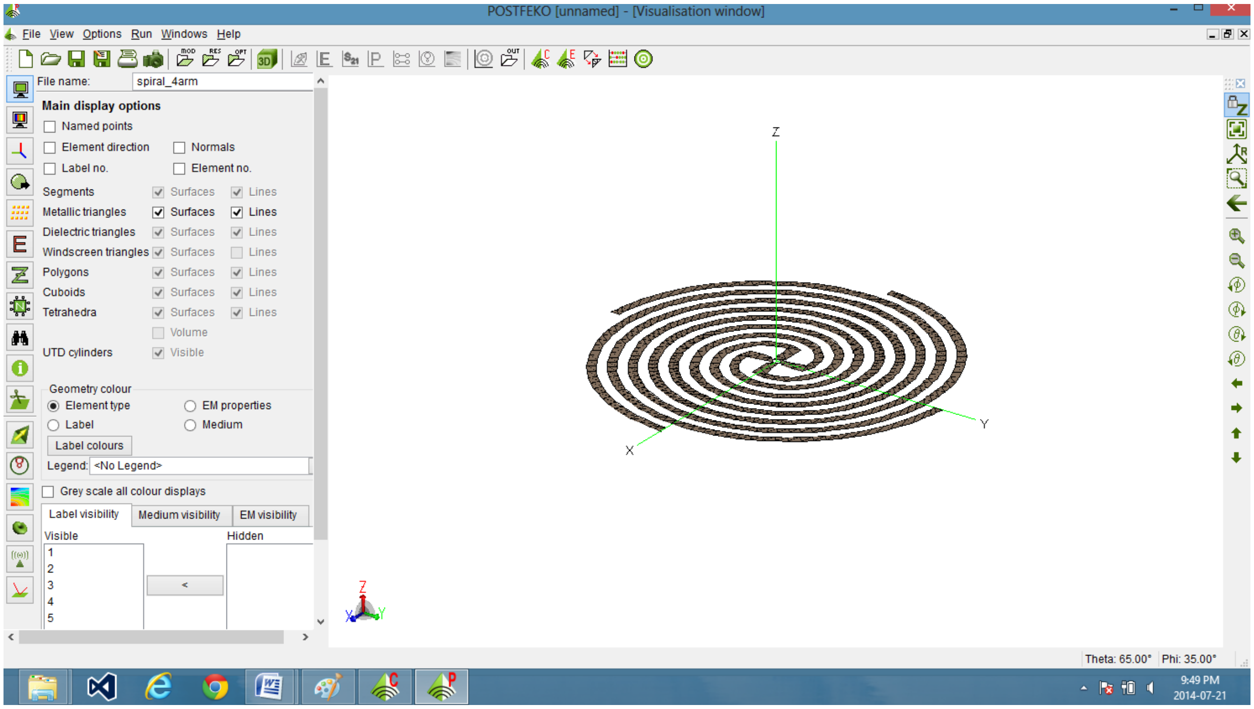
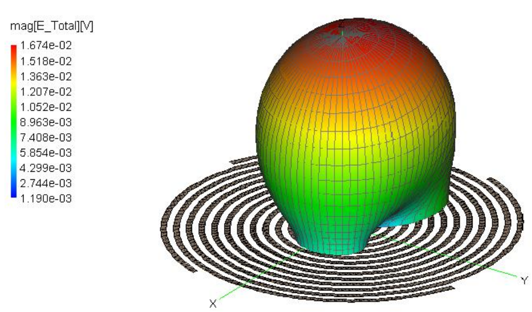


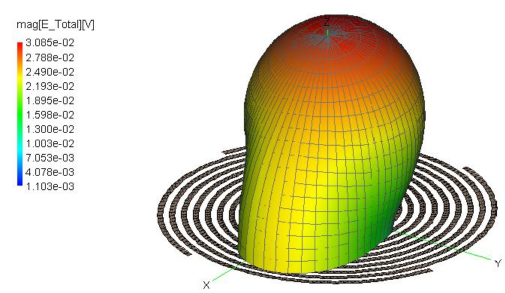
Figure 6.3-b Spiral antenna model designed in Editfeko

6.4 Result and Discussions

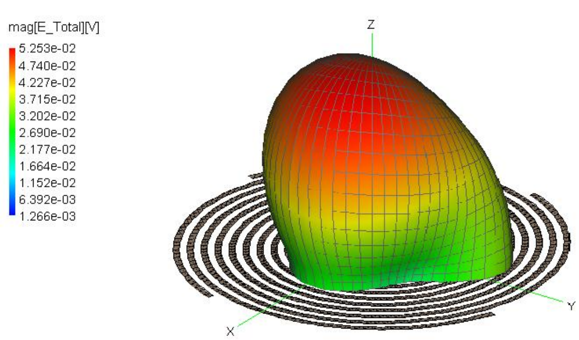
Results of above designed models are listed as:



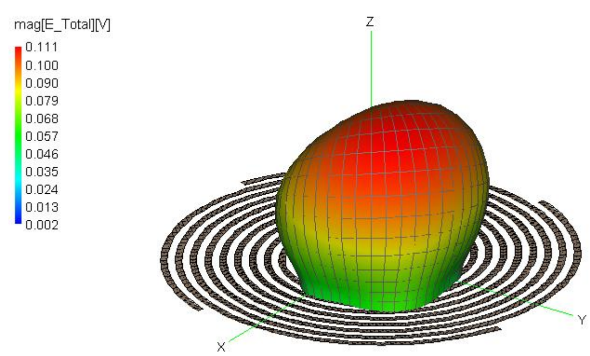
(a)



(b)



(c)



(d)

Figure 6.4-a 3-D Radiation Pattern of spiral antenna (a) 2GHz (b) 3GHz (c) 5GHz (d) 6GHz

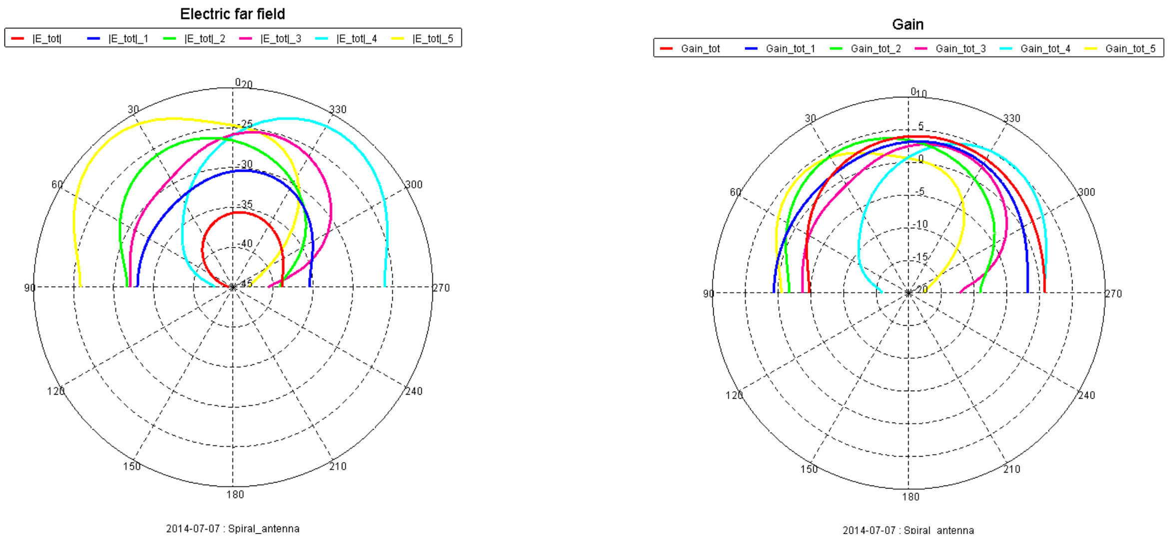


Figure 6.4-b Polar plot of Gain and electric field of Spiral antenna

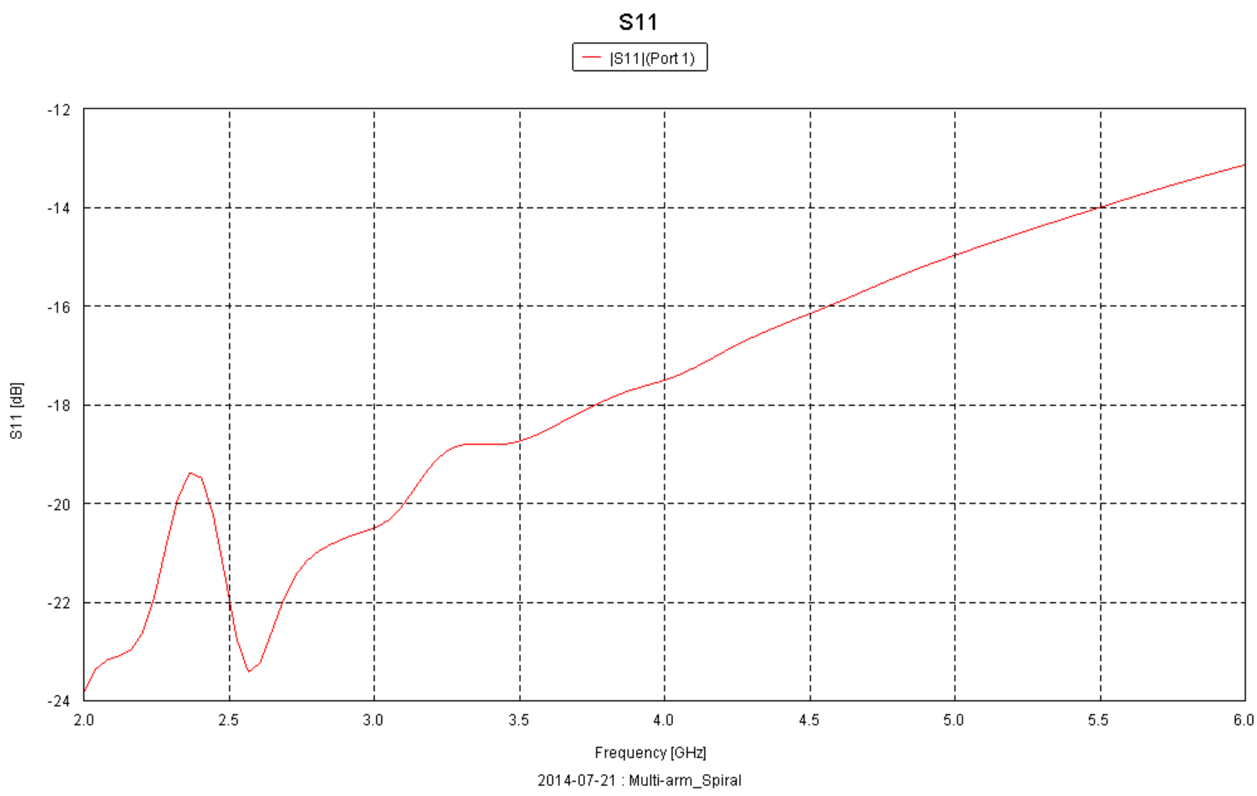


Figure 6.4-c Return loss of spiral antenna

Figure 6.4-d shows the reflection coefficient from 2 GHz to 6 GHz. The reference impedance is chosen to be 1775.5 according to Babinet principle. Antenna is showing very good behavior from 2 GHz to 6 GHz. Initially return loss is found to be -24 dBi, at 6 GHz return loss id found to be -13 dBi.

7. Spiral Mode Microstrip Antenna

7.1 Introduction

Spiral mode microstrip antenna is a recent variation on the conventional spiral antenna. This antenna does not require a cavity backing behind the spiral; rather, it operates similar to a microstrip line in what is called the spiral microstrip mode. This allows the antenna to become quite thinner and lighter as compared to the conventional spiral. Also, it permits feeding the spiral arms in-phase for mode-0 operation yielding a monopole like pattern. This antenna has also been utilized as a multifunctional antenna[42] for car where the mode-0 is used for terrestrial communication and mode-1 for satellite communication. The spiral is fed from a broadband mode-forming network where mode-1 and mode-2 are excited simultaneously with arbitrary relative phase difference.

7.2 Prior Art

The spiral modes, specifically modes-1, 2, and 3, have been known for four decades and have been well exploited in the widely used cavity-loaded spiral antennas[43]. However, cavity-loaded spirals use absorbing materials to dissipate radiation on the other side of the spiral, therefore are bulky and

[42] Eberhard Gschwendtner and Werner Wiesbeck,"Ultra-Broadband Car Antenna For Communication And Navigation Applications", IEEE TRANASACTION ON ANTENNAS AND PROPAGATION, VOL. 51 NO. 8 AUG 2003
[43] R.G. Corzine and J.A. Mosko, Four-Arm SpiruZ Antennas, Artech House, Norwood, MA, 1990.

lose one- half of their power in the dissipative cavity. For these antennas, mode-0 has been mentioned in the literature as the case in which all the spiral arms are excited in equal amplitude and phase. However, mode-0 has not been implemented because the spiral arms excited with the same phase and amplitude constitute null generators between them and thus transmit and receive no power. The spiral-mode microstrip (SMM) antenna[44] makes mode-0 operation meaningful and practical because signals with equal voltage and phase on all spiral arms can now be referenced to a common ground plane inherent in the SMM antenna[45]. As a result, implementation of mode-0 operation of the SMM antenna has been applied to multifunction shared aperture antennas[46] [47]; however, the bandwidth achieved was only 20 to 100 %, depending on the performance criteria.

7.3 Design and simulations

Spiral mode microstrip antenna design is similar to conventional spiral antenna except substrate upon which spiral microstrip are added. The height of substrate will affect the radiation pattern of the antenna. Feed is given at relative phase according to requirement of mode. Four sources are fed out-of-phase. Thus, for a current at a location on the first arm, the current at the corresponding point on the second arm is out-of-phase by the phase which the excitation phase differs. The outer loads are used to decrease the current on the uttermost turns. The inner loads reduce the current on the center which improve the return loss. The axial ratio is also

[44] J.J.H. Wang and V.K. Tripp, “Design of Multioctave Spiral-Mode Microstrip Antennas,” IEEE Trans. Ant. Prop., Vol. 39, March 1991.
[45] Johnson J. H. Wang, James K. Tillery, and Michael A. Acree, “Multioctave Wideband Mode0 Operation of Spiral-Mode Microstrip Antennas”.
[46] J.J.H. Wang, V.K. Tripp, and J.K. Tillery, “Conformal Low-Profile Multifiinction Antennas,” 1995 AP-S Symposium, June 1995.
[47] J.J.H. Wang, ‘‘Conformal Multifunction Shared-Aperture Antennas,” U.S. patent 5,508,710, April 16, 1996.

improved by eliminating return waves which have an opposite polarization. Archimedean spiral is formed by spiral equations. Fundamental equation of Archimedean spiral is, r=a ϕ.

Phase for different modes of a 4 arm spiral antenna:

Arms	Mode 0	Mode 1	Mode 2	Mode 3
Arm 1	0^0	0^0	0^0	0^0
Arm 2	0^0	90^0	180^0	240^0
Arm 3	0^0	180^0	360^0	540^0
Arm 4	0^0	270^0	540^0	810^0
Relative phasing	0^0	90^0	180^0	270^0

Relative phase between the arms,ϕ, is given by

$$\phi = \frac{360m}{n}$$

Where n is the number of arms and m is the number of mode. ϕ is in degrees.

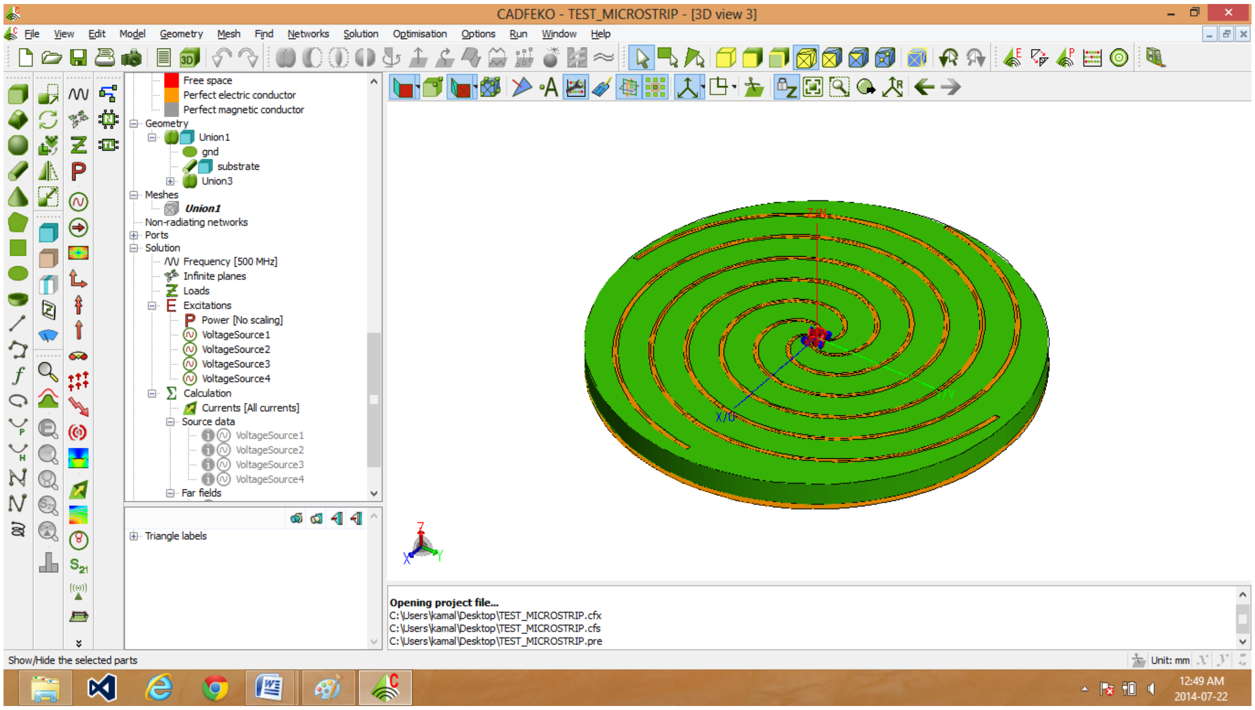


Figure 7.3-a Spiral mode microstrip antenna designed model in Feko

7.4 Result and Discussion

Results of simulation in Feko are given as below. Due to complexity of mode forming network I couldn't achieve the wideband mode forming network. Various modes are obtained as a result of applying different phase of input.

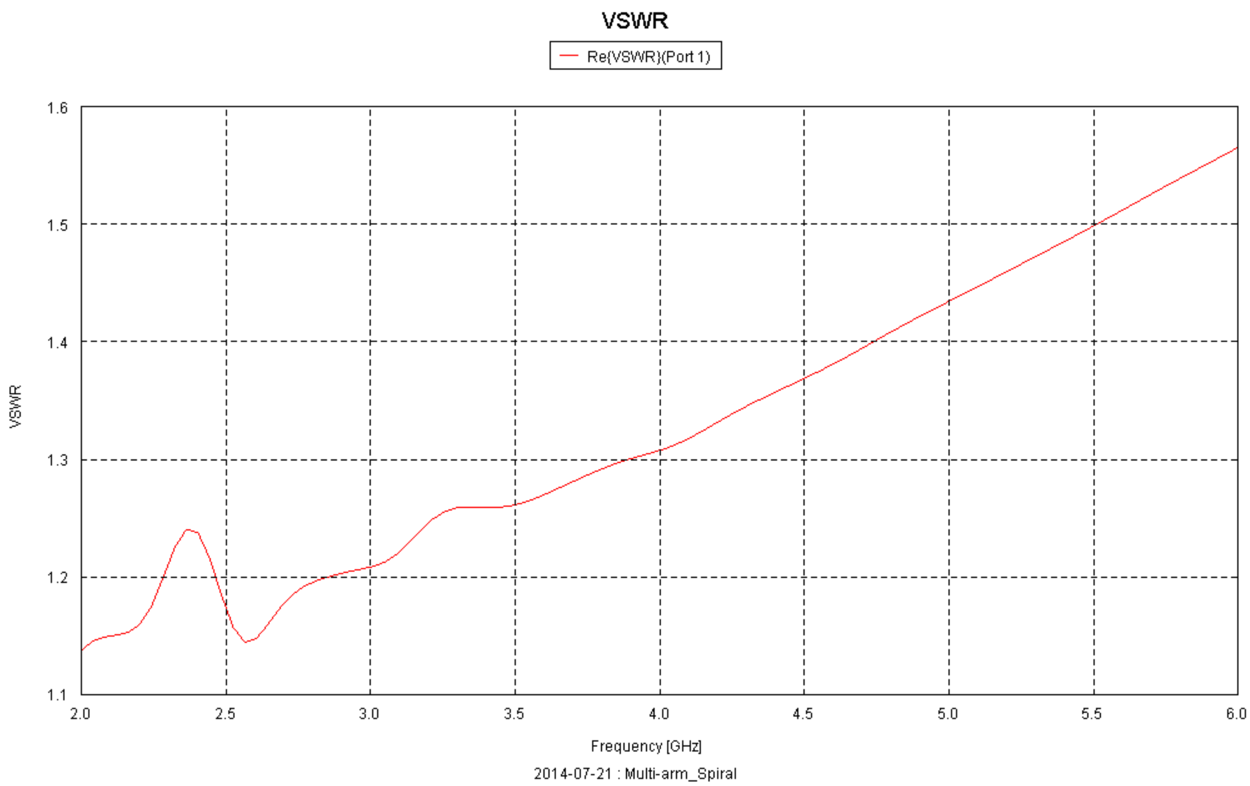
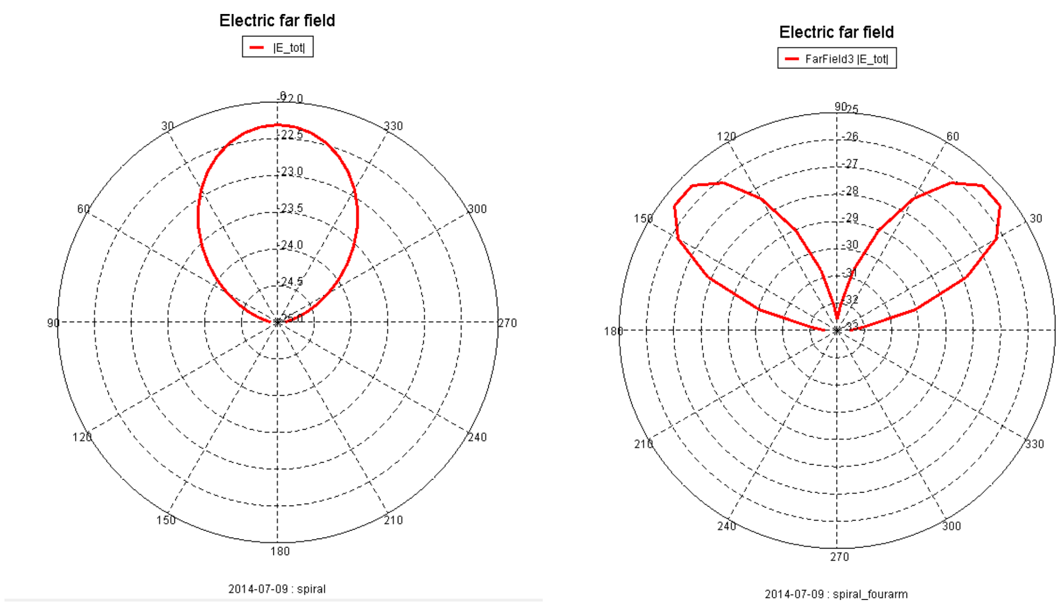


Figure 7.4-a VSWR plot of spiral-mode microstrip antenna



(a) (b)

Figure 7.4-b (a) Mode-1 2-D radiation pattern (b) Mode-2 Radiation Pattern

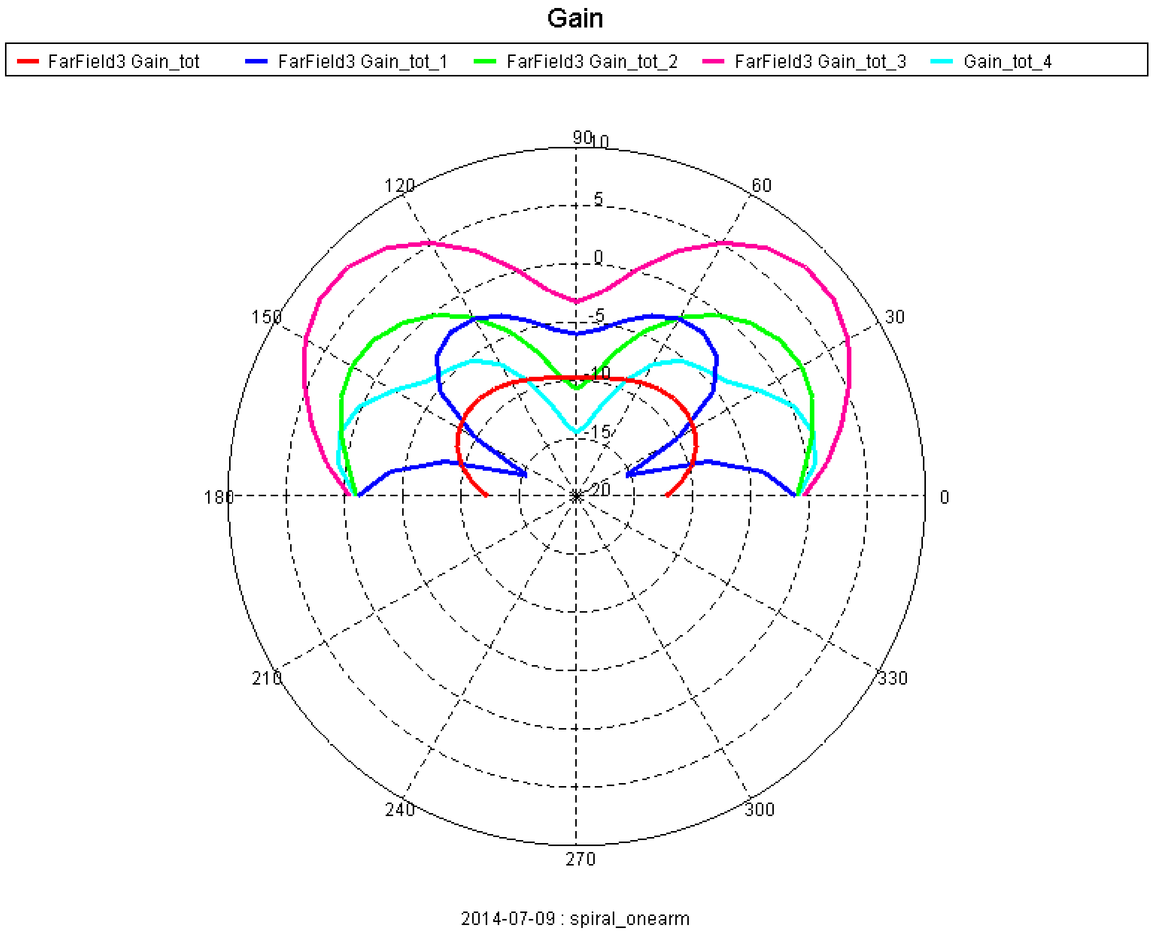


Figure 7.4-c Placements of nulls in different modes

Conclusion

Four wideband antennas have been studied for realizing wideband coverage. The simulation results for all antennas are provided and discussed in the respective chapter. Four different antennas namely Vivaldi antenna, Sinuous Antenna, Spiral Antenna, Micro-strip mode Spiral Antenna were simulated. Vivaldi antennas showed remarkable performance over the entire frequency range of 2.5 GHz to 4 GHz with return loss to be 1.2 and gain 10 dBi. Similarly sinuous antenna and spiral antenna showed good performance in terms of return loss, directivity and gain. The wideband multi arm spiral mode microstrip antenna has been shown to operate as a conformal, multifunctional antenna with multiple beams covering the entire hemisphere. This antenna can also be used for an application such as angle of arrival estimation and adaptive nulling at the element level.

Future Work

All discussed antenna can be improved more with different feed mechanism to correctly match the input impedance. The entire simulated antenna can be optimized to use for aircraft structure for wideband hemispherical coverage. Vivaldi array can be formed to obtain the complete coverage for LOS and BLOS requirements. Spiral antenna may be exploited to advantage in state-of-the-art array configuration by further studying the feasibility of array design using this wideband element in a 2-arm or multi-arm implementation.

Appendix

(A) Matlab code to generate exponential taper profile in Vivaldi antenna. Generated Matlab structures' co-ordinates are transferred using ginput() function.

```
x1=-50;
x2=50;
y1=1;
y2=40;
r=input('taper rate');
c1=(y2-y1)/((exp(r*x2))-(exp(r*x1)));
c2=((y1*(exp(r*x2)))-(y2*(exp(r*x1))))/((exp(r*x2))-(exp(r*x1)));
disp(c1);
disp(c2);
x=[-45:45];
A=(c1*(exp(r*x)))+c2;
plot(x,A);
hold on;
A=-((c1*(exp(r*x)))+c2);
plot(x,A);
hold off;
```

(B) Editfeko code to generate spiral antenna

```
**  Spiral parameters
#a = 1.1459                ** Spiral growth constant (r = a*phi)
#w = 1                   | ** Strip width
#m = 4.37                  ** Number of turns
#ri = 3                    ** Inner strip start radius
#ro = #ri + #w             ** Outer strip start radius
#phi1 = #ro/#a             ** Start angle (radians)
#phi2 = #phi1 + 2*#pi*#m   ** End angle (radians)

**  Global edge length
#tL0 = min(#lam/12,1.5*#w)
IP                                        #tL0

**  Compute length of spiral
#L1 = #a*(#phi1*sqrt(1 + #phi1^2) + ln(#phi1 + sqrt(1 + #phi1^2)))/2
#L2 = #a*(#phi2*sqrt(1 + #phi2^2) + ln(#phi2 + sqrt(1 + #phi2^2)))/2
#L = #L2 - #L1

**  Construction parameters
#ds0 = 0.4*#tL0                    ** Start segment length
#ds1 = 2*#tL0                      ** End segment length
#b = (#L - #ds0)/(#L - #ds1)       ** Segment growth factor
#k = ceil(ln(#ds1/#ds0)/ln(#b)+1)  ** Approximate number of segments required
#ds0 = #L*(#b-1)/(#b^#k-1)         ** Compute new start segment length based on number of segments

**  Initialise loop variables
#ds = #ds0
#phi = #phi1
#dphi = #ds/(#a*sqrt(1+#phi^2))
#phi = #phi + #dphi
#r = #a*#phi

**  Create first data points
#r0 = #r
#r1 = #r - #w
#x0 = #r0*cos(#phi-#phi1)
#y0 = #r0*sin(#phi-#phi1)
#x1 = #r1*cos(#phi-#phi1)
#y1 = max(#r1*sin(#phi-#phi1),#w/2)
```

Bibliography

[1] P. J. Gibson. The Vivaldi aerial [J]. 9th Europe Microwave Conference.1979. 101~105.

[2] R. H. DuHamel, “Dual Polarized Sinuous Antennas,” U.S. Patent 4658262, April 14, 1987.

[3] Four-arm spiral antennas, Corzine .R. G & J.A Mosko. 1990, Norwood, MA, ArtechHouse.

[4] Eberhard Gschwendtner and Werner Wiesbeck,”Ultra-Broadband Car Antenna For Communication And Navigation Applications”, IEEE TRANASACTION ON ANTENNAS AND PROPAGATION,VOL. 51 NO. 8 AUG 2003

[5] Richard J.Barton, Peter J. Collins, Paul E.Crittenden, Miachel J. Havrilla, Andrew J. Terzuoli, “Acompact Passive Broadband Hexagonal Spiral Antenna Array for VHF Remote Sensing”, IGARSS, page 593-595, IEEE, 2007
[6] FEKO, Comprehensive Electromagnetic Solutions, S.A
[7] C. A. Balanis, Antenna Theory : Analysis and Design, 3rd ed. New York: John Wiley and Sons, Hoboken, NJ, 2005.
[8] J. D. Kraus, Radio Astronomy. New York: McGraw-Hill, 2002
[9] J. D. Kraus and R. J. Marhefka, Antennas. New York: McGraw-Hill, 2002.
[10]V. H. Rumsey, “Frequency independent antennas,” IRE National Convention Record, vol. 5, pp. 114–118, 1957.
[11] K. Louertani, R. Guinvarc’h, N. Ribiere-Tharaud, and M. Darces, “Design of a spiral antenna with coplanar feeding solution,” Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE, pp. 1–4, 2008.
[12] Y. T. Lo, “A mathematical theory of antenna arrays with randomly spacedelements,” IEEE Transactions on Antennas and Propagation, vol. 12, pp. 257–268, 1964.
[13] P. J. Gibson, “The Vivaldi Aerial,” Proc. 9th European Microwave Conference, Brighton, U.K., Oct. 1979, pp. 101- 105.
[15] L. R. Lewis, M. Fasset, and J. Hunt. “A broadband stripline array,” IEEE A P-S Synip., June 1974, p. 335.
[16] E. Gazit, “Improved design of a Vivaldi antenna,” IEEE Proc. H, April 1988, pp. 89-92.
[17] B. Schuppert, “Microstrip/Slotline Transitions: Modeling and Experimental Investigation,” IEEE Transactions on Microwave Theory and Techniques, Vol. 36, No. 8, August 1988, pp. 1272-1282.
[18] R. Sloan, M. M. Zinieris, L. E. Davis, “A broadband microstrip to slotline transition,” Microwave and Optical Technology Letters, Vol. 18, No. 5, August 1998, pp. 339-342.
[19] D. H. Schaubert, J. Shin, “A Parameter Study of Stripline-Fed Vivaldi Notch Antenna Arrays,” IEEE Transactions on Antennas and Propagation, Vol. 47, No. 5, May 1999, pp. 879-886.
[20] Greenberg, M. C., L. Virga, and C. L. Hammond, “Performance characteristics of the dual exponentially tapered slot antenna for wireless

communication application," IEEE Trans. on Vehicular Technology, Vol. 52, 305–310, Mar. 2003.

[21] Antenna Engineering Handbook,Ch.24, Ultra wideband Arrays by J.J. Lee, Raytheon space and Airborne systems, McGraw-Hil.

[22] R. H. DuHamel, "Dual Polarized Sinuous Antennas," U.S. Patent 4658262, April 14, 1987.

[23] M. C. Buck and D.S. Filipović, "Split-Beam Mode Four-Arm Slot Sinuous Antenna," Antennas and Wireless Propagation Letters, Volume 3, Issue 1, 2004 Page(s): 83 - 86.

[24] R. C. Johnson, Antenna Engineering Handbook, Chapter 14, pp. 14-1 - 14-68, Third. Edition, McGraw-Hill, 1993.

[25] M. C. Buck, A. Bhobe, and D.S. Filipović, "A Flush-Mounted Multi-Band/Broadband Sinuous-Like Slot Antenna for Terrestrial Communications," URSI National Radio Science Meeting, June 2003.

[26] M. C. Buck and D.S. Filipović, "Split-Beam Mode Four-Arm Slot Sinuous Antenna," Antennas and Wireless Propagation Letters, Volume 3, Issue 1, 2004 Page(s): 83 - 86.

[27] M. C. Buck, J. Burford, and D.S. Filipović, "Multiband Two Arm Slot Sinuous Antenna," IEEE Antennas and Propagation Society Symposium Proceedings, Volume 1, 20-25 June 2004 Page(s): 165 – 168.

[28] Kamaljeet Singh Saini and Richard F. Bradley , "The Sinuous Antenna A dual polarized element for wideband phased array feed application", February 13, 1996

[29] H . G. Booker: "Slot. Aerials and Their Relation to Complimentary Wire Aerials (Babinet's Principle)." JJEE(London), pt.IIIA. pp.620-627, 1946.

[30] R. H. DuHamel, "Dual Polarized Sinuous Antennas," U.S. Patent 4658262, April 14, 1987.

[31] Joseph A. Mosko, 'An Introduction to Wideband, Two-Channel Direction-Finding Systems I, II, ' Microwave Journal, February 1984

[32] Daeyoung Oh, Myungki Kim & Ikmo Park, 'Two-Arm Microstrip Spiral Antenna With A Circular Aperture On The Ground Plane ,' Microwave Communication Laboratory, Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea

[33] J.D. Muller and K. Sarabandi, Design and Analysis of a 3-arm spiral Antenna, IEEE Trans. Antennas Propagation, Vol 55, PP.258-266, Feb.2007.

[34] D. G. Shively and W. L. Stutzman, “Wideband arrays with variable element sizes,”Microwaves, Antennas and Propagation, IEE Proceedings H, vol. 137, no. 4, pp.238–240, August 1990.
[35] W. L. Stuzman, “Wide bandwidth antenna array design,” Proceeding of the IEEE Southeastern Regional Meeting, Raleigh,NC, pp. 92–96, 1985.
[36] J. Thaysen, K. B. Jakobsen, and H. R. Lenler Eriksen, “Wideband cavity backed spiral antenna for stepped frequency ground penetrating radar,” vol. 1B, 2005, pp. 418–421.
[37] H. Nakano, K. Nogami, S. Arai, H. Mimaki, and J. Yamauchi, “A spiral antenna backed by a conducting plane reflector,” Antennas and Propagation, IEEE Transactions on, vol. 34, no. 6, pp. 791–796, 1986.
[39] B. Wang and A. Chen, “Design of an Archimedean spiral antenna,” 8th International Symposium on Antennas Propagation and EM Theory 2008 ISAPE 2008, pp. 348–351, 2008.
[40] J. H. Wang and V. K. Tripp, “Design and simulation of a planar archimedean spiral antenna,” IEEE trans on antennas and propagation, vol. 39, no. 3, March 1991.
[41] H. Nakano, T. Igarashi, H. Oyanagi, Y. Iitsuka, and J. Yamauchi, “Unbalanced-Mode Spiral Antenna Backed by an Extremely Shallow Cavity,” Antennas and Propagation, IEEE Transactions on, vol. 57, no. 6, pp. 1625–1633, 2009.
[42] Eberhard Gschwendtner and Werner Wiesbeck,”Ultra-Broadband Car Antenna For Communication And Navigation Applications”, IEEE TRANASACTION ON ANTENNAS AND PROPAGATION, VOL. 51 NO. 8 AUG 2003
[43] R.G. Corzine and J.A. Mosko, Four-Arm Spiral Antennas, Artech House, Norwood, MA, 1990.
[44] J.J.H. Wang and V.K. Tripp, “Design of Multioctave Spiral-Mode Microstrip Antennas,” IEEE Trans. Ant. Prop., Vol. 39, March 1991.
[45] Johnson J. H. Wang, James K. Tillery, and Michael A. Acree, “Multioctave Wideband Mode0 Operation of Spiral- Mode Microstrip Antennas”.