ARCHIMEDEAN SPIRAL ANTENNA EMBEDDED WITH FREQUENCY SELECTIVE SURFACE FOR WIDEBAND APPLICATIONS

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ABSTRACT

The potential applications such as satellite communication systems, critical military communications, radar warning systems and direction finding systems demand for high gain, uniform unidirectional radiation pattern and wideband antenna ranging from 3.1 GHz to 10.6 GHz. An Archimedean spiral antenna is the most potential candidate in the above mentioned applications as the antenna meets most of the above requirements. However, the practical implementation of spiral antenna is challenged by its bidirectional patterns, relatively low gain and the need for balanced feeding structures. A moveable ground plane is proposed as the backing technique of the spiral antenna by placing it at quarter wavelength behind spiral arms. Despite, the effects of the ground plane on the antenna's wideband properties, to enable the realization of a conformal antenna without the loss of the antenna's broadband characteristics, a radian sphere theory is proposed for bandwidth improvement. Microstrip to parallel strip line balun is proposed as the feeding structure of the spiral antenna. This balun has very large bandwidth ranging from 2 GHz to 14 GHz. However, the separation of the ground plane and the spiral arms at quarter wavelength at lower frequencies deteriorate the radiation patterns at middle and higher frequencies. In order to improve the patterns, frequency selective structure is proposed to embed in the cavity of the spiral antenna. The optimized frequency selective surface improves the radiation pattern while maintaining the other parameters such as the gain, bandwidth and axial ratio. All the proposed designs are fabricated and measured. Both simulated and measured results have shown good agreements. Finally, the results show that the proposed Archimedean spiral antenna is the most suitable candidate for above mentioned applications because good circularly polarized unidirectional radiation patterns and high gain of 8 dB to 11.2 dB with bandwidth of more than 140% is obtained.

ABSTRAK

Aplikasi berpotensi seperti sistem komunikasi satelit, komunikasi tentera kritikal, sistem amaran radar dan sistem mencari arah mempunyai permintaan untuk keuntungan tinggi, corak sinaran satu arah seragam dan jalur lebar antena daripada 3.1 GHz kepada 10.6 GHz. Antena lingkaran Archimedes adalah calon yang paling berpotensi untuk memenuhi sebahagian besar daripada keperluan aplikasi tersebut.Walau bagaimanapun, pelaksanaan prototaip antena lingkaran sangat mencabar disebabkan oleh corak dwiarah, agak keuntungan yang rendah dan keperluan teknik pengujaan yang seimbang. Satah pembunian bergerak dicadangkan sebagai teknik sokongan antena lingkaran dengan meletakkannya pada jarak suku daripada panjang gelombang di belakang lingkaran.Kesan penggunaan satah pembumian terhadap ciri-ciri jalur lebar adalah untuk membolehkan antenna komformal direalisasikan tanpa kehilangan ciri-ciri jalur lebar itu,teori sfera radian adalah dicadangkan untuk peningkatan jalur lebar. Mikrojalur ke balun talian jalur selari dicadangkan sebagai teknik pengujaan antena lingkaran. Balun ini mempunyai lebar jalur yang sangat besar di antara 2 GHz hingga 14 GHz. Walau bagaimanapun, pemisahan satah pembumian dan lengan antena lingkaran pada panjang gelombang suku pada frekuensi rendah memberi kesan buruk pada corak sinaran pada frekuensi pertengahan dan tinggi.Untuk meningkatkan corak sinaran, struktur frekuensi terpilih dicadangkan untuk menanamkan rongga di dalam antena lingkaran. Nilai optimum struktur frequensi terpilih memperbaiki corak sinaran sambil mengekalkan parameter lain seperti keuntungan, jalur lebar dan nisbah paksi. Semua reka bentuk yang dicadangkan menjalani proses fabrikasi dan pengukuran. Kedua-dua keputusan simulasi dan pengukuran menunjukkan persamaan yang baik. Akhirnya, keputusan menunjukkan antena lingkaran Archimedes yang dicadangkan itu adalah calon yang paling sesuai untuk aplikasi yang dinyatakan di atas kerana baik keliling polarisasi corak sinaran satu arah dan keuntungan tinggi 8 dB kepada 11.2 dB dengan lebar jalur lebih daripada 140% diperolehi.

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Publications

Proceedings

i. A. M Shire and F. C. Seman "Effects of dielectric substrate on performance of UWB Archimedean Spiral Antenna" Space Science and Communication (IconSpace), 2013 IEEE International Conference Pages 412-415.
ii. Abdirahman Mohamud Shire and Fauziahanim Che Seman "Analysis of the Active Region of Archimedean Spiral Antenna" Chapter 25, Notes Electrical Eng., Vol. 315, et al: Advanced Computer and Communication Engineering Technology.
iii. Abdirahman Mohamud Shire and Fauziahanim Che Seman "Parametric Studies of Archimedean Spiral Antenna for UWB Applications" PRESENTED at Apace Conference, 10 December 2014.

Journals

iv. F. B. Zarrabi, A. M. Shire, M. Rahimi and N. P. Gandji "Ultrawideband tapered patch antenna with fractal slots for dual notch application" Microwave Optical Technology Letters, Vol. 56, 2014, Pages:1344-1348.
v. F. C. Seman and A. M Shire "Archimedean Spiral Antenna on Moveable Ground Plane for UWB Applications" (Under Review at APRN Journal; indexed in SCOPUS).
vi. A. M Shire and F. C. Seman "Numerical Analysis of Frequency Selective Surface Using Equivalent Circuit Method" (Under Review at electronic letters)

List of Awards

i. GOLD PRIZE “Archimedean Spiral Antenna on Moveable Ground Plane” Exhibited at the Seoul International Invention Fair (SIIF) 2014, in Seoul, South Korea.

ii. SILVER MEDAL “Archimedean Spiral Antenna on Moveable Ground Plane” Invention and Innovation Awards for Malaysia Technology Expo (MTE) 2014, in Kuala Lumpur, Malaysia.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Wide band is a transmission technology in which information is transmitted over large operating bandwidth. Such technology has been utilized for decades mostly for military related systems because more information and applications can be carried through the radio frequency channels with a high data rate and accuracy [1]. Wideband applications are numerous including ground penetrating radar systems, military communications, satellite communications, direction finding systems, vehicular radar systems and wireless communications [2]. In order to make the transmission and reception of an wide band system over the frequency range of 3.1 GHz to10.6 GHz; it is required to have a high gain antenna, with good impedance matching and VSWR less than 2 throughout the entire band [2-3]. Therefore, Archimedean spiral antenna is good candidate to be used in wideband applications since it has met the above mentioned requirements. Archimedean spiral antenna has received huge interest over the last two decades due to its wide impedance bandwidth, high efficiency, nearly unidirectional radiation pattern, low profile, stable impedance characteristic and circular polarization over the last two decades [4].

There are three different designs of spiral antennas. The first design of spiral antenna is by shaping it as a single arm spiral antenna, which is designed for some narrow-band applications. The second design is the two arm case, which is the minimum number of arms needed for single-mode broadband operation. The third design is the multi arm case, which is designed when two broadband modes are needed. This means, in order to achieve two broadband modes at least three arms are required. Therefore, in this research the second design which is the two arm case is discussed due to its advantages over the other two cases. It is because the two arm Archimedean spiral antenna has better axial ratio than the single arm Archimedean spiral antenna, which means the two arm case has better circular polarization compared to the single arm case. The two arm spiral antenna has a simple feed (e.g. Microstrip to parallel strip balun) and less complex geometry design compared to the multi arm spiral. It is because the multi arms spiral has complex geometry design and feeding systems such as a beam feeding network.

In summary, several optimizations techniques are proposed in this study such as loading lower permittivity dielectric substrate, radian sphere concept, reducing mutual coupling, moveable ground plane and embedding frequency selective surface structure in the cavity of the spiral. Therefore, these five optimization techniques leads to the invention of a new design of two arm Archimedean spiral antenna backed by cavity with large bandwidth, high gain, unidirectional pattern with circular polarization and with higher efficiency.

1.2 Problems Statement

A common approach used to cover a large frequency range which encompasses many different communication systems is to employ a separate antenna for each system.

An advantage of this approach is that it meets the specific needs of each communication system. However, when a platform such as an airplane, ship or automobile requires the use of many communication systems, this approach has several problems such as space, payload, cost and electromagnetic compatibility/interference (EMC/EMI). Therefore, there is a significant interest in antennas which possess compact size, have multi-functional characteristics, have large bandwidth (>20%) and have high gain.

In the design of an antenna that meets the above requirements, there are several challenges that must be taken into account. First of all, the antenna must have sufficient bandwidth to facilitate the integration of multiple antennas into a single aperture. Since the applications of interest require bandwidths in excess of 10:1, this work focuses on wide-band antenna such as the Archimedean spiral antenna. Since the spiral antenna belongs to the class of frequency independent antennas, it is easily capable of bandwidth greater than 10:1 [5]. Such antennas are considered frequency independent because their pattern, impedance and other parameters vary little with frequency as compared to a multi-band antenna which can exhibit considerable variation. These characteristics make the spiral an ideal candidate for replacing a variety of antennas. Apart from the advantages of spiral antenna, there are disadvantages in spiral antenna, such as the spiral antenna has a low gain and bidirectional radiation pattern. There are several techniques to get rid of the bidirectional radiation pattern, such as by using an absorber-filled cavity, a lossy cavity, and conducting ground plane.

Therefore, in this project a technique is proposed to get rid of this problem, which is to construct a moveable ground plane, which maintains quarter wavelength spacing between the spiral and the ground plane in the vicinity of the active region of the spiral. However, by introducing this technique; antenna's patterns at higher frequencies deteriorate. In order to improve the patterns and to minimize the splitting of the patterns at higher frequencies; a frequency selective surface structure is embedded between the spiral antenna and the ground plane. This new design can substantially enhances the radiation pattern properties of the antenna since the reflected field is in phase with that directly radiated by the antenna itself. In addition, by embedding the FSS structure in the design minimizes the gain fluctuations caused by the ground plane. However, FSS structure together with the ground plane reduces the antenna's bandwidth. One way to minimize the FSS reduction of the bandwidth is applying the radian sphere theory in order to make the antenna electrically larger and to obtain larger bandwidth.

As a result of the optimized techniques such as the ground plane (for unidirectional radiation pattern), radian sphere theory (for maintaining wideband bandwidth) and embedding FSS in the cavity of the spiral antenna (for better performance of radiation pattern), it is expected to come up with new spiral antenna prototype, which has enhanced unidirectional radiation pattern, wide bandwidth (at least 100% of bandwidth of return loss better than -10dB) and high gain which enables the antenna to detect the enemy radar in a large range of distance compared to the present radar systems.

1.3 Research Contribution

Throughout this research work several major contributions have been achieved for Archimedean spiral antenna performance. In this section a summary of these major contributions are presented:

1. A prototype of wideband Archimedean spiral antenna has been designed with enhanced performance based on *Radian sphere theory*.
2. Universal design of spiral antenna has been used which leads to the elimination of multiple antennas configurations on wideband systems.
3. A tapered microstrip to parallel strip lines balun is proposed with new tapered design based on mathematical formulation is proposed as a feeding technique for wideband antennas.
4. Comprehensive study is carried out for different structures of frequency selective surface in order to improve the antenna's performance.

5. Band stop frequency selective surface design based numerical synthesis is developed.

1.4 Objectives of Study

This project has the following objectives:

i. To design wideband Archimedean spiral antenna on a moveable ground plane placed at a quarter wavelengths for selected design frequencies in order to achieve high gain antenna with circularly polarized unidirectional radiation pattern.

ii. To design and embed frequency selective surface structure in the Archimedean spiral antenna cavity in order to improve antenna's radiation pattern performance.

1.5 Scope of Study

This project focuses on the performance investigations of Archimedean spiral antenna based on radian sphere theory, FSS structures and microstrip to parallel strip balun within wideband frequency range (3.1-10.6GHz). The effects of the dielectric materials (free space ε_r=1, Rogers RT 5870 ε_r=2.33, FR-4 ε_r= 4.3 and Rogers RO3030 ε_r=10.2) and moveable ground plane placed at quarter wavelengths for selected design frequencies including 2GHz, 3.1GHz, 5GHz, 6.85GHz and 10.6GHz on the performance of the spiral antenna are investigated, in order to achieve a bandwidth of 100% at the return loss of the antenna; which below -10dB, high gain of up to 10dB and unidirectional radiation pattern with circular polarization using discrete port as the feeding of the antenna. Wideband balun such as microstrip to parallel strip lines balun over the frequency range of 2 GHz to 14 GHz as the feeding network of the antenna is designed. Square loop of FSS structures with reduced periodicity are designed. Commercially available computer model of CST microwave studio 2012 has been used for simulation and investigations for the performance of spiral antenna, balun and FSS structures. In order to validate the theoretical analysis, the antenna, FSS and balun structures are fabricated on dielectric substrate; Rogers RT 5870 with permittivity of ε_r=2.33 and thickness of 1.57mm. Finally, the measurements of the required characteristics such as S11, S21 and gain are carried out using vector network analyzer.

1.6 Dissertation Overview

This thesis is divided into 7 main chapters and a reference section. Chapter I discusses about the introduction, problem statement, objectives and scope of the project. In Chapter II, literature review of Archimedean spiral antenna, wideband balun and FSS are discussed. For Chapter III, the methodology of the project, mathematical formulation of the spiral antenna, balun and FSS are discussed. Similarly, the numerical analysis of the active region of the two arm Archimedean spiral antenna is documented. In addition, the fabrication and measurement processes of the spiral antenna, balun and FSS are elaborated. In Chapter IV, the results of spiral antenna on a moveable ground plane based on discrete port and balun feedings are analyzed. Likewise, the results of the optimization techniques of the spiral antenna such as Radian sphere theory, reducing mutual coupling, loading lower permittivity substrate, analysis of the active region are also documented. While the analysis of the balun, integration of spiral antenna with balun and comparison of the measurement and simulation results of spiral antenna on a moveable ground plane are highlighted in Chapter V. The simulation results of FSS for different shapes and dielectric substrate, the embedding of FSS in the cavity of spiral antenna, the optimized results of the FSS and its combination with spiral antenna, the comparison results of the simulation and numerical analysis of FSS and the measurement and simulation of spiral antenna embedded with FSS are analyzed in

Chapter VI. Chapter VII discusses about the conclusion and recommendation of the future work, while the last section highlights the references of this dissertation.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter elaborates spiral antenna as frequency independent antennas, some of the previous works related to spiral antenna, backing techniques of spiral antenna, feeding technique of spiral antenna and Frequency selective surface structures. Wideband wireless communications offers a drastically distinctive approach to wireless communications contrasted with traditional narrow band systems. Wideband has provoked a surge of investment in antenna design by furnishing new challenges and opportunities for antenna architects. The primary challenge in wideband antenna design is accomplishing the wide bandwidth while maintaining high gain, high radiation efficiency and good axial ratio over a very wide frequency range. Archimedean spiral antenna is a good candidate for wideband applications since it is a broadband and frequency independent antenna that has high efficiency, wide bandwidth and circular polarization. Unidirectional Archimedean spiral antenna is designed by placing the antenna on a ground plane. The ground plane reflects back the backward radiation from the spiral plane; and then by adding it with the radiation from the spiral plane into free space in phase [5]. The use of ground plane deteriorates the bandwidth, axial ratio and the radiation pattern at higher frequencies. Then the use of the radian sphere theory and frequency selective surface structures are required to potentially improve the performance of the spiral antenna.

2.2 Spiral Antenna as a Frequency Independent Antenna

In 1954, although discouraged by many experts, E. M. Turner wound a long-wire dipole into a spiral form and connected its terminals to a two-wire feed line [6-11].At that time, the largest antenna bandwidths were on the order of one octave, but the results obtained with the first spiral experiment were so encouraging that an immediate research effort was launched. Octave bandwidth implies that the higher frequency (f_H) of operation is double the lower frequency (f_L), for example, an antenna that works from 2GHz to 4GHz has one octave bandwidth [6]. At the present time, wideband frequency independent antennas are irreplaceable components of many communication platforms, various electronic warfare, military communication, satellite communication, direction-finding systems and atmosphere, ground and space exploration stations [5]. In this work, the term wideband indicates on the frequency bandwidth (*Bf*) either in ratio ($Bf=f_H/f_L$) or fractional bandwidth (*Bf in percentage is* $Bf= (f_H-f_L)/f_C$) and $f_C=f_H+f_L/2$). Frequency independent (FI) antenna is a type of antenna in which its pattern, bandwidth, gain and other characteristics vary insignificantly with frequency [5]. Spiral antenna is good example for FI antennas and its bandwidth can reach up to 40:1 for both the input impedance and the radiation pattern [12].

Spiral antennas are classified into several types; square spiral, star spiral, Archimedean spiral and equiangular spiral. The square spiral antenna has the same advantages as circular Archimedean spiral antenna at the lower frequencies. But the square spiral geometry seems to be less frequency independent at higher frequencies [13]. A star spiral provides as much size reduction as the square spiral and it allows tighter array packing that the square spiral does not allow [13]. However, one of the major disadvantages of the star spiral antenna is its dispersive behavior [13]. Equiangular spiral antennas have similar characteristics of the Archimedean spiral antenna but their design is more complex compared to circular Archimedean spiral antennas. Therefore, in this project, circular Archimedean spiral antenna is chosen due to its wide bandwidth, frequency independent characteristics and simple design compared to the other types of spiral antennas. Figure 2.1 illustrates examples of the wideband frequency independent spiral antennas.

(a) (b) (c)

Figure 2.1: Examples of two arm Spiral Antenna: (a) Archimedean Spiral, (b) Equiangular Spiral and (c) Square Spiral [13].

2.3 Characteristics of Antenna

There are important antenna parameters which are return loss, radiation pattern, gain and polarization. All of the aforementioned antenna parameters are necessary to fully characterize an antenna and determine whether an antenna is optimized for its applications.

2.3.1 Return Loss

Return loss is the reflection of signal power resulting from the insertion of a device in an antenna structure or a transmission line. Return loss measurements include the characterization of the Voltage Standing Wave Ratio (VSWR). Increasing return loss corresponds to lower VSWR. According to the wideband requirement; return loss is a measure of how well the antenna is matched and a match is good if the return loss is more less than -10dB [14]. Minimum return loss is also desirable and results in a lower insertion loss. Insertion loss is the loss of signal power resulting from the insertion of a device in that structure. Return loss indicates the bandwidth for which the antenna sufficiently works along its entire frequency range. Figure 2.2 shows the return loss of wideband antenna and the working bandwidth of the antenna is the region between 1 and 2.

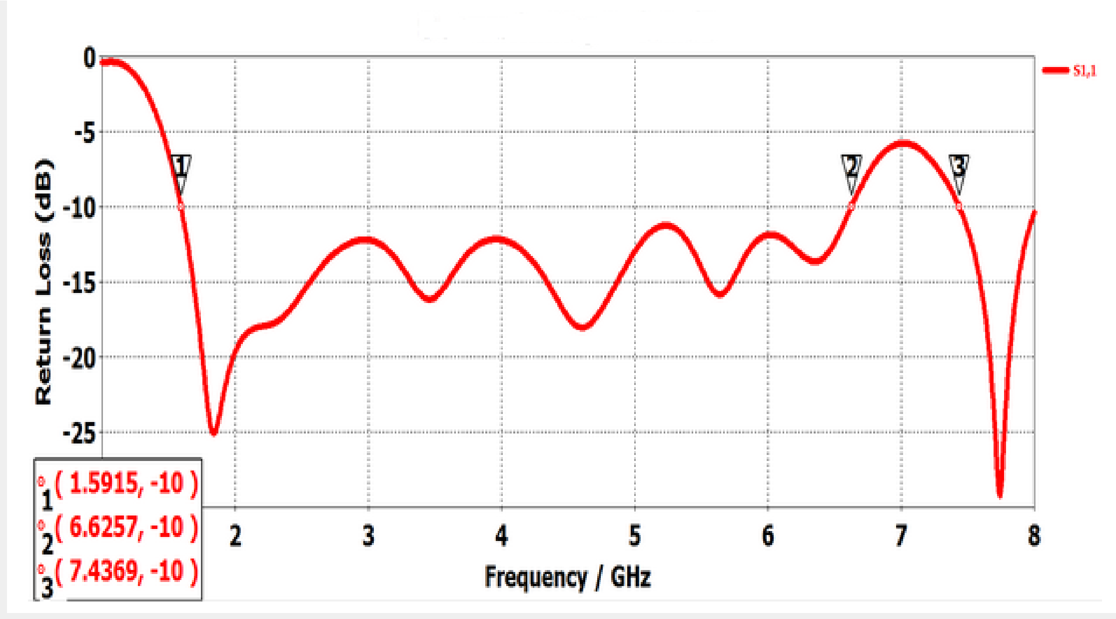
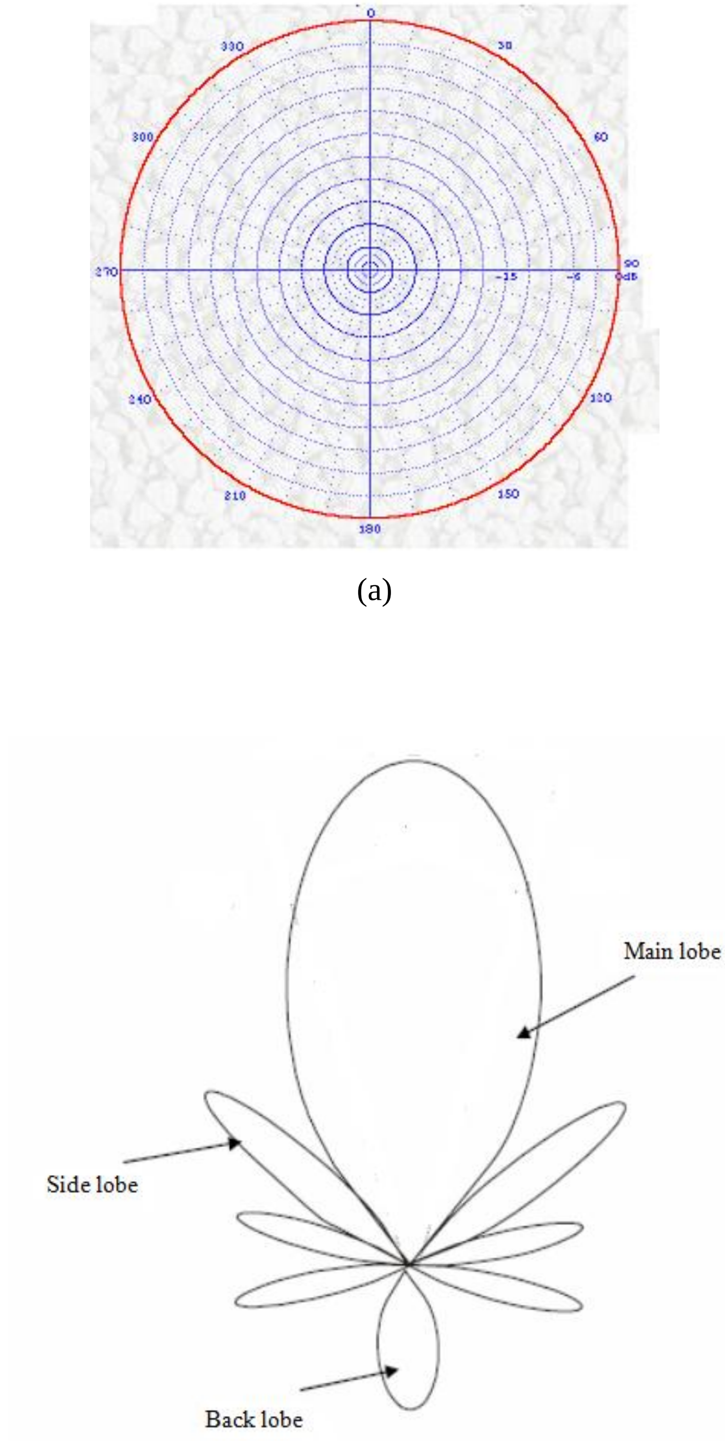


Figure 2.2: The return loss of Wideband antenna [14]

2.3.2 Radiation pattern

One of the most common descriptors of an antenna is its radiation pattern. Radiation pattern can easily indicate an application for which an antenna will be used. For example, cell phone use would necessitate a nearly omnidirectional radiation pattern as shown in Figure 2.3 (a), as the user’s location is unknown. Therefore, radiation power should be spread out uniformly around the user for optimal reception. However, for satellite or military applications, a highly directive antenna would be desired such that the majority of radiated power is directed to a specific, known location, hence unidirectional radiation pattern is shown in Figure 2.3 (b).

According to the IEEE Standard Definitions of Terms for Antennas [14], an antenna radiation pattern (or antenna pattern) is defined as the variation of the power radiated by an antenna as a function of the direction away from the antenna. The main properties of the pattern are side lobes, back lobes and main lobes. In practice, it is impossible to eliminate antenna side lobes and back lobes completely. Antenna side and back lobes affect antenna system performance in several ways. The energy delivered to or received by side and back lobes is from a direction other than the intended region of coverage and is therefore wasted [14]. Main lobe is the radiation lobe containing the direction of the maximum radiation. The side lobe is a radiation lobe in any direction other than the intended lobe direction. It is usually adjacent to the main lobe and occupies the hemisphere in the direction of the main beam while the back lobe is in the opposite direction.



(a)

(b)

Figure 2.3 Radiation Patterns: (a) Omni-directional and (b) Unidirectional [14].

2.3.3 Gain

Gain is the most widely used descriptor for antenna performance. The gain is defined as the ratio of power received by a directional antenna to power received by an isotropic antenna [14]. An isotropic antenna is a theoretical antenna radiating energy equally in all direction of space. The gain of an antenna must equal to its directivity if the antenna 100% efficient. The gain of an antenna is therefore less than the directivity due to the losses in the antenna. Gain which referred to an isotropic radiator is expressed as “dBi”.

In addition, the gain of the proposed spiral antenna can be expressed in mathematical formulation in terms of the known radiated power per unit area on the bore sight of the antenna $P_{rad}\,(r,\phi,\theta,\omega)$ and the power inserted into the spiral P_{in}. If the current and impedance at the feed point are denoted I_{in} and Z_{in}, respectively, ω is the angular frequency of the radiated power, while r,ϕ and θ are the spherical coordinates of the antenna, one may use Equations (2.1-2.4) to write the gain; G [14-15]:

$$Z_{in} = \eta_o/2 \tag{2.1}$$

$$P_{in} = \frac{(I_{in}{}^2)(Z_{in}{}^2)}{2} \tag{2.2}$$

$$P_{rad}\,(r,\phi,\theta,\omega) = \frac{\left(E_r(r,\phi,\theta=0,\omega)\right)^2}{2\eta_o} = \frac{\left(\omega\mu_{o\lambda}I_{in}\right)^2}{(8\pi r)^2\eta_o} \tag{2.3}$$

$$G = 4\pi\frac{P_{rad}}{P_{in}} = \frac{\pi\eta_o(I_{in})^2}{2(I_{in}Z_{in})^2} \tag{2.4}$$

2.3.4 Polarization

Antenna polarization is a very important consideration when choosing and installing an antenna. Most communications systems use vertical, horizontal or circular polarization. Knowing the difference between polarizations and how to maximize their benefit is very important to the antenna user. The electric field or "E" plane determines the polarization or orientation of the radio wave. In general, most antennas radiate either linear or circular polarization [14]. A linear polarized antenna radiates entirely in one plane containing the direction of propagation. An antenna is vertically polarized (linear) when its electric field is perpendicular to the Earth's surface and horizontally polarized (linear) when its electric field parallel to the Earth's surface as shown in Figure 2.4.

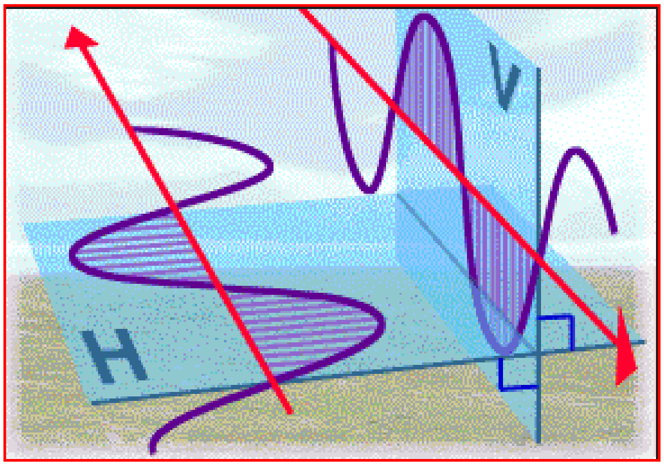
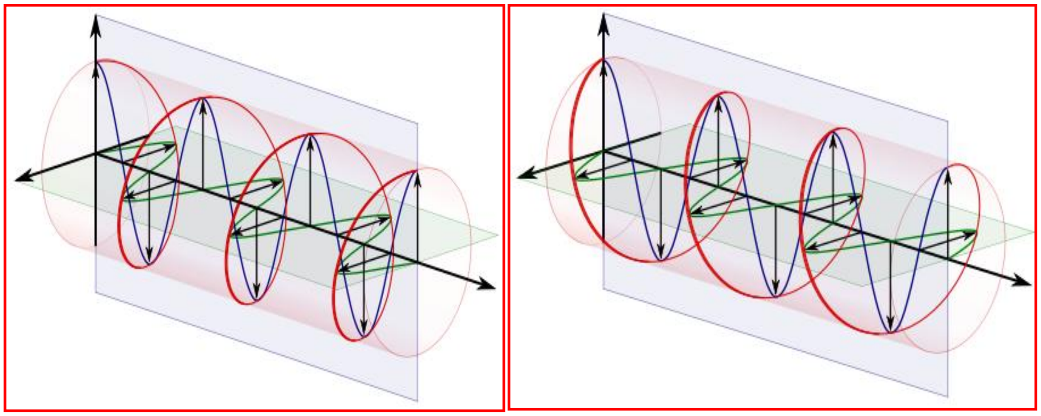


Figure 2.4: Linear Polarization; V stands for Vertical Polarization while H is for Horizontal Polarization [14].

In a circular polarized antenna, the plane of polarization rotates in a circle making one complete revolution during one period of the wave. If the rotation is clockwise looking in the direction of propagation, the sense is called right-hand-circular (RHC). If the rotation is counterclockwise, the sense is called left-hand-circular (LHC) [14]. A circular polarized wave radiates energy in both the horizontal and vertical planes and all planes in between. The difference between the maximum and the minimum peaks as the antenna is rotated through all angles, is called the axial ratio and is usually specified in decibels (dB). If the axial ratio is near 0 dB, the antenna is said to be circular polarized. However, still an axial ratio of less than 3dB can be accepted for circular polarization. Circular polarization is most often used on satellite communications, critical military communications, direction finding systems and GPS.



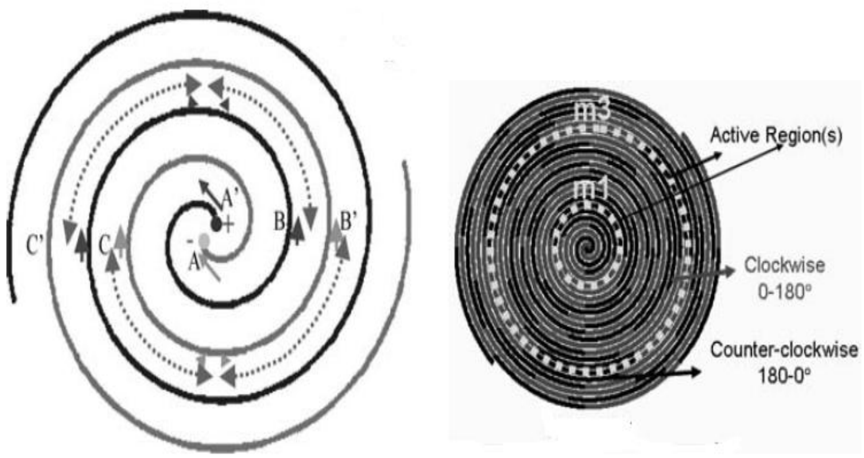
(a) (b)

Figure 2.5: Circular Polarization: (a) Left Hand Polarization and (b) Right Hand Polarization [14].

2.4 Basic Principles of Operation for Spiral Antenna

The representation of the current distribution on the arms of the spiral permits to visualize the active region of the spiral radiator. The surface current densities on the spiral arms are retrieved from the near zone field distribution. Generally, the current distribution is analyzed as pulse excitation and harmonic excitation. But in this research, only harmonic excitation is considered. The current density distributions on the spiral at particular frequencies in steady-state are discussed in Chapter IV; section 4.3.1.The current distribution of the spiral antenna qualitatively demonstrates the concept of frequency dependent active region of where the radiation process is taking place on the Archimedean spiral [15].

The radiating ring theory, also known as band theory is used to describe the theoretical principles behind the operation of spiral antennas [15]. The band theory is demonstrated on the simplest and most commonly used spiral antenna; a two-arm, planar spiral antenna operating in mode 1. As depicted in Figure 2.6 (a) the spiral is fed from its center at ports A and A’, ideally with equal amplitudes and a 180° phase difference.



(a) (b)

Figure 2.6: Band theory: (a) Mode 1 excitation and (b) Phase of the traveling wave current [15].

When fed with a balun, the two spiral arms at the spiral center is a balanced current pair-one arm is 180^0 out of phase with the other arm and the spiral will support propagation of the forward traveling wave. Mode 1 radiation will predominantly occur from a ring with approximately one guided wavelength (λ) circumference [16]. When excited to operate in this mode, spiral currents at points B and B', which belong to neighboring arms, will be directed the same way, for example they will have the same phase value. The same is true for diametrically opposite points C and C'. The non-radiated traveling wave currents will flow past this region, and if the size of the spiral permits, radiate in the next properly phased section. This will occur at a circumference equal to three wavelengths (mode 3 for a two-arm spiral) as shown in Figure 2.6 (b). If the spiral is not large enough, the currents will reach the end of the spiral arms where they are either absorbed or reflected back toward the spiral's center. Note that if the size of the spiral is large enough, the in-phase current conditions will show up at odd wavelength circumferences of the spiral and higher order modes will radiate. This condition is known as overmoding [17]. Similarly, the phase of the traveling wave current is shown in Figure 2.6 (b), where two different shadings denote the instantaneous phases between 0–180° and 180–0°. The mode regions with currents directed the same way are clearly seen.

The mode 1 phase has a single rotation -2π in the full counterclockwise rotation of a spiral pattern; mode 2 has a –2(2π) phase rotation, and so on [18]. The mode number of a spiral refers to the number of 2π (radians) or 360^0 cycles that occur in the feed phasing when progressing through the arms CCW. Mode 1 phases in a two-arm spiral are 0^0 or 180^0 as shown in Figure 2.6 (a) and (b). The phase difference moving CCW between arms is found from the mode number m and the number of arms n.

$$\mathrm{phase} = \frac{-2\pi \mathrm{m}}{\mathrm{n}} \mathrm{or} - \frac{360^0 \mathrm{m}}{\mathrm{n}} \tag{2.5}$$

The spiral radiates RHC polarization for m=1 using the notation of Equation (2.5) when it is fed at the center. An axially symmetrical antenna such as a spiral can radiate these modes when we phase the feeding of the ports to match the phase rotation of the mode [19-20]. Given a spiral with n arms, the modes that have significant radiation are a multiple of the number of arms when fed with a perfect beam former network as stated in the following equation:

$$\mathrm{m}_{\mathrm{radiated}} = \mathrm{m} + \mathrm{kn} \quad \mathrm{k} = \cdots, -2, -1, 0, 1, 2, \ldots \tag{2.6}$$

n-arm spiral suppresses n-1 modes between possible modes given that the spiral circumference is large enough to support a particular mode. For example, a six-arm spiral excited in mode 1 will radiate modes 1, 7, 13, …, -5, -11, … and when excited in mode 2 it will radiate modes 2, 8, 14, …, -4, -10, …, and so on. Good radiation pattern is achieved if the antenna radiates sufficient power in the lower-order modes since small amount of power is left for the higher-order mode radiation and that will lead to the antenna for better radiation patterns [21, 22].

Although these characteristics and basic principles are good start for the designing a frequency-independent wideband antenna, employing these characteristics alone does not necessarily produce a wideband FI antenna design. Other antenna design considerations such as the dielectric loading, Radian sphere concept, mutual coupling, moveable ground plane and embedding FSS in the spiral’s cavity, must be taken into account.

2.5 Techniques for Performance Optimization of Spiral Antenna

There are several techniques which can be used to optimize the performance of wideband spiral antenna such as the loading dielectric substrate, radian sphere concept, mutual coupling, moveable ground plane and embedding FSS (moveable ground plane and embedding FSS are discussed under backing techniques):

2.5.1 Dielectric Loading Effects

A spiral is a fast wave antenna and the use of a high dielectric constant or thick dielectric can significantly alter its characteristics. Input resistance is reduced and the gain, axial ratio, and pattern purity in general are all degraded when compared with a free standing spiral. Dielectric loading slows the traveling wave thus reducing the aperture of the active mode. Additionally, the coupling between the neighboring arms is increased and the radiation through the active region is decreased. This means that the forward traveling wave, after passing the desired region, will have more energy and radiate in the higher order modes, contributing to the excessive far-field contamination [23]. Therefore, in order to improve antenna’s performance a lower permittivity and less thick substrate are chosen for this proposed antenna in this project. Effects of dielectric loading are best shown in Chapter IV, section 4.2. Studies show that when high permittivity dielectric substrate is used; the performance of the antenna deteriorates. This is due to the high permittivity substrate which assimilates more input power fed to the antenna and leads to the poor performance of the antenna [23].

2.5.2 The Radian Sphere Concept

Antennas perform poor effective radiation which leads to a general poor performance of the antenna if the antenna's dimensions are much less than one wavelength. This poor performance limits the antenna's applications in practical aspects. The "radiansphere" is the boundary between the near field and the far field of a small antenna. An electrically small antenna is often defined using the concept of the radian sphere [24]. The radian sphere is a hypothetical sphere whose diameter 2r is equal to the largest linear dimension of the antenna that it encloses.When the electrical size of the radian sphere is less than λ (or $r \leq \lambda/2\pi$), the antenna enclosed by the sphere is considered to be electrically small.These antennas exhibit low radiation resistance, high reactance, low efficiency and narrow bandwidth and all of these parameters limit the performance of the antenna. These antennas are subject to limitations which are fundamentally about the same for a capacitor used as an electric dipole and an inductor (loop) used as a magnetic dipole, if they occupy equal volumes. Either type may have some advantages resulting from variations within this rule or from relative facility in coupling with the associated circuits [24].

The radiation pattern and hence the directive gain of a small antenna remain the same for a smaller size, the radiation resistance decreases relative to the other resistance in the coupling circuit. The resulting reduction in coupling efficiency is one of the principal limitations of the smaller antenna. Another aspect of the same limitation relates to the frequency bandwidth of operation with fixed values of the circuit elements. A smaller antenna with the same reactance and radiation resistance must be more sharply tuned to deliver its available power. Therefore, the reduction of size imposes a fundamental limitation on the bandwidth. If the bandwidth so limited is insufficient, further damping must be added at the expense of coupling efficiency. The limitations verify the experience that larger antennas are generally more efficient, especially for wide band operation. By expressing the formulas in fundamental forms; the inherent similarity of the electric and magnetic radiators becomes apparent, as well as the minor differences resulting from the use of available materials and structures [24]. Therefore, having known these limitations, a simple mathematical synthesis of the active region based on the radiansphere technique is developed, which leads to the design of electricaly large spiral antenna for wideband applications.

2.5.3 Mutual Coupling

Mutual coupling between adjacent arms of spiral antenna affects both the radiation patterns and the bandwidth [5]. The radiation from one driven arm induces currents on other nearby arm and scatters into the far field, which causes poor performance. Continuous and stable antenna characteristics across an wide bandwidth require a smooth transition from one active region to the next as frequency varies. This implies a strong coupling between adjacent structures. In the case of a spiral antenna, this requires sufficient arm spacing to the mutual coupling between the neighbor arms of the spiral antenna, which causes undesired fluctuations in gain, pattern, and return loss.

2.6 Previous Works on the Spiral Antenna

The application of the spiral antenna in satellite communication systems, radar detection, direction-finding and military communication systems causes it to appear in a wide variety of works. These are Rumsey's work on frequency independence, Kaiser's paper, Dyson's1957thesis, and the paper on the same work [7, 18, 25 and 26]. One of the first published attempts at analyzing the spiral was by Curtisin1959 [27]. In that work, the two-arm spiral was approximated by a series of connected thin-wire semicircles. The model showed good agreement with experimental results when the antennas were made in the same semi-circular shape. In 1961, Cheo, Rumsey, and Welch published an analytical work in which the spiral element was approximated with an "infinite arm" spiral [28]. In 1963, Sivan-Sussman showed experimentally that two-arm, four-arm, and six-arm spiral radiation patterns shown one of the characteristics seen in the infinite spiral solution when fed in a similar way [29].

Some of the earliest purely experimental works on the spiral were by Bawer and Wolfe [30-31]. They consisted of papers in 1960 and 1961 that described the design of spiral antennas on printed circuit boards and the use of an absorbing can to create a unidirectional pattern. This appears to be the first work to propose the use of a dielectric backing material for the spiral. Prior works formed the spiral shape by cutting slots out of thick metal sheets. Bawer and Wolfe's papers were criticized by Dyson for lumping the Archimedean spiral in with the equiangular spiral in [32]. However, from a design point of view the equiangular spiral does not appear to share a great deal with the Archimedean spiral.

The spiral has been a subject of a number of numerical works, but is often presented as verification for a numerical technique rather than the subject of the work itself. A very early computerized application of the Method of Moments by Mei in 1964 [33] used the spiral as an example. Here the current on a thin-wire spiral was computed as an example of the utility of the method. Another example is an early application of the finite-difference time-domain (FDTD) method to antennas in 1994 by Luebbers. He analyzed two spiral antennas over an absorbing can [34]. Modeling the spiral with an extremely small feed attached to a self- complementary bow-tie tends to show the predicted value for the impedance.

In 2006, Fumeaux, Baumann, and Vahldieck published an analytical work in which the spiral element was backed by cavity and analyzed through Finite-Volume Time Domain [35]. While not physical, the solution did show a current that dropped off rapidly, suggesting an active region for the antenna. The spiral sustains good performs such as a bandwidth 126% and unidirectional radiation pattern with circular polarization as shown in Table 2.1. However, antenna's efficiency is low around 60% while gain fluctuates from -2dB to 6dB. The reason for this poor gain performance is due to the backing technique in which they used cavity filled with absorber material and this absorber leads to the spiral antenna with low gain and efficiency performances. The design of this paper is illustrated in Figure 2.7.

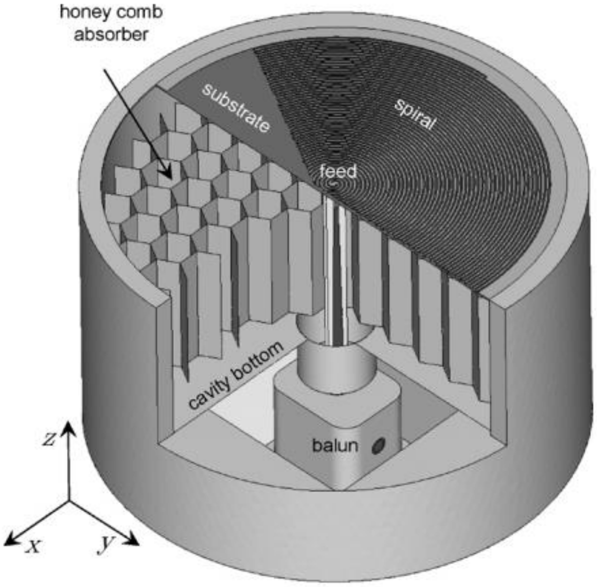


Figure 2.7: Spiral antenna on a cavity loaded with the honeycomb absorber [35].

The absorber-loaded cavity behind the spiral suppresses un-desired back radiation of the spiral. The cavity (around 22 mm) deep is filled with a honeycomb absorber with hexagonal cells arranged as shown in Figure 2.7. The honeycomb structure itself is coated with a resistive material. The resistivity is graded, with an increase toward the bottom of the cavity to maximize absorption. Obviously, the absorber lowers the efficiency of the antenna by about 40%. The same analysis goes to the work done by Nakano, Kikkawa, Iitsuka and Yamauchi in 2008 [36] and Guraliuc and Caso in 2012 [37]. Figure 2.8 shows the design of Nakano’s work and consists of an antenna and ring absorber material which is embedded between the spiral antenna and the ground plane cavity.

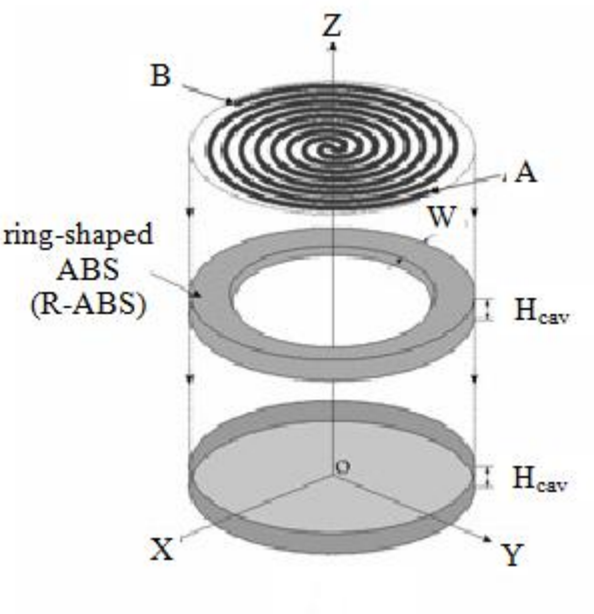


Figure 2.8: Archimedean Spiral Antenna with ring absorber material [36].

While directly addressed in this thesis, one active area of research regarding the spiral antenna is in making the antenna pattern unidirectional. This is typically achieved by attaching an absorbing can to the back of the antenna, but this reduced half of the energy inserted into the spiral and requires a significant amount of space. Because of this, a number of authors have proposed methods to reflect the radiation. This has generally been achieved by placing some type of planar reflector behind the spiral. In recent work by Nakano, two reflectors are described. In 2009, Nakano and Nogami presented spiral antenna backed by a conducting ground plane reflector [38], in which the gain and the efficiency performances is better compared their work in [36] as shown in Table 2.1, while the bandwidth is only about 108% and the reason of this lower bandwidth is the GP reflector without absorber. However, the work in this dissertation is contrast to previous researches that focused on either large bandwidth with lower gain and efficiency or narrow bandwidth with higher gain and efficiency. Because large bandwidths, high gain, high efficiency and uniform unidirectional radiation patterns through out of the entire bandwidth are obtained. In summary, comparison of the recently works of spiral antenna and with the proposed backing techniques are shown in Table 2.1.

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