

LOW PROFILE SPIRAL ANTENNAS OVER AMC GROUND PLANES

By

ALI MOMEN MEHRABANI

A Thesis
Submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements
for the degree of

Master of Science

Department of Electrical and Computer Engineering
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**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of
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Of

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ABSTRACT:

A spiral antenna has a broadside circularly polarized radiation pattern with a wide beamwidth at its fundamental mode. These properties are highly demanded in wireless communication systems such as spread spectrum, multifunction radio frequency systems, and airborne direction finding. Advancements in these applications have increased the demand for low-profile antennas. In recent decades, the development of artificial magnetic conductors (AMC) has opened a new window in low-profile applications, since these surfaces can be used as a ground plane at reduced distances to a planar antenna without sacrificing the antenna radiation performance.

In this thesis, low profile circular curl and dual-arm Archimedean spiral antennas are studied using a finite artificial magnetic conducting ground plane. These antennas generate circularly polarized waves with an excellent circular polarization performance. The distance between each antenna and the artificial ground plane is reduced to $0.02\lambda_0$ at the operating frequency of 4.5GHz. The overall gain and axial ratio of the designed low profile antenna are comparable with those of the same antenna over a conventional perfect electric conductor (PEC) ground plane at a distance of $0.25\lambda_0$. The artificial ground plane consists of periodic square patches backed by a grounded dielectric slab. Ground planes as small as 4×4 square patches are used without shorting vias. The planar size of the artificial ground plane is about $0.837\lambda_0\times 0.837\lambda_0$. To have a physically robust structure, each antenna is printed on a dielectric slab, which is placed over the artificial ground plane. Comprehensive design parametric studies are completed to understand their effects on the overall performance of the antenna.

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Chapter 1

Introduction

1.1 Preface

In recent years, development of Electromagnetic Band-Gap (EBG) structures has led to significant advancements in low profile antenna applications. EBG structures have the potential to minimize the size of an antenna, while improving its radiation characteristics. Mushroom like EBGs were first introduced by Sievenpiper [1]. Such a structure attracted the attention of researchers in antenna and microwave community, because it provides high impedance surfaces with a zero reflection phase over a specific frequency band, as well as a propagation bandgap. EBG surfaces can be used in filters, traveling wave amplifiers, and in particular, as ground planes in low profile antenna applications. These surfaces may consist of periodically arranged metallic patches over a grounded dielectric slab [2].

The current study investigates single and dual arm spiral antennas over artificial magnetic conductor (AMC) ground planes. An AMC is a high impedance surface like an EBG, except it may support surface waves. The main goal is to develop low profile circularly polarized antenna structures by situating the radiating element very close to the ground plane, without sacrificing antenna performance. These type of antennas produce circularly polarized (CP) waves over a traditional ground plane at a minimum distance of a quarter-wavelength. In this work, the antenna height, the distance between the top surface of the AMC and the antenna, is reduced to a small fraction of wavelength of $0.02\lambda_0$.

1.2 Literature Review

Advancements in mobile communication technology have increased the demand for low profile antennas. In other applications such as navigation systems, low-profile antennas with low blockage and mutual interference can facilitate improved system performance with small sizes. Furthermore, aerodynamic structures such as aircrafts may also implement low-profile antennas for various purposes [3].

In the aforementioned applications, circularly polarized waves are required since linear polarization will be difficult to align, particularly for handheld terminals that are operated in random orientation. The spiral antenna, due to its circularly polarized radiation pattern, is a well-known candidate for such applications. The concept of spiral antennas was first introduced by Edwin Turner in the mid 1950s [4]. Turner's results provided an insight into the development of mathematical analysis for the frequency independent antennas by Victor Rumsey in 1957 [5].

A spiral antenna has a bidirectional radiation pattern. In most applications a unidirectional radiation is required. A ground plane, such as a planar metal sheet, can be used for these applications. The ideal ground plane is a perfect electric conductor (PEC), which has a reflection coefficient of +1 and -1 for vertical and horizontal polarizations, respectively. Therefore, if a planar antenna is placed very close to the ground plane, the far-field radiation from the image current will cancel that of the antenna [6]. Thus, the cancellations of the far-field radiations degrade the antenna radiation efficiency. For low profile antennas, the degradation of antenna radiation may be alleviated by using a perfect magnetic conductor as a ground plane. Magnetic conductors can be engineered using periodic structures, like electromagnetic band-gap structures, EBG. Such surfaces,

near their resonant frequency, fully reflect incident waves with a near zero degree reflection phase and can also suppress the propagation of surface waves. Assuming no losses and an exactly zero reflection phase, the surface is referred to as a perfect magnetic conductor (PMC), which is complementary to a perfect electric conductor (PEC). The first EBG structure was invented by Sievenpiper in 1999 [1]. It is well-known as a mushroom like EBG structure, which provides a high impedance surface with a zero tangential magnetic field over the band-gap frequency range. When considering the manufacturing process, such structures can be easily fabricated using the printed-circuit-board technology. Under certain circumstances, they can also be analyzed using lump-element circuit models [1]. Essentially, EBG consists of a periodic array of arbitrarily shaped patches backed by a grounded dielectric slab. In a mushroom like EBG structure, patches are connected to the ground plane through vias. There are other types of EBG structures, based on different geometrical shapes of the patches. One example is a uniplanar compact EBG (UC- EBG) studied and analyzed in [7-9]. Another example is a spiral unit cell which was investigated in [10-12]. One more example is a split ring resonator, which was introduced and analyzed in [13-14].

There are a few publications on low-profile spiral antennas over EBG structures. In [15], a low profile dual-arm squared spiral antenna over a mushroom like EBG structure was investigated. The distance between the antenna and the EBG surface was minimized to $0.06\lambda_0$ with a ground plane size of $2.16\lambda_0 \times 2.16\lambda_0$ at the resonant frequency of 6GHz. The EBG structure consisted of an array of 10×10 square patches backed by a grounded dielectric slab. A four-element array of square spiral antenna with an EBG ground plane was also designed for low profile applications [16]. An axial ratio (AR) less than 3dB

was obtained over a bandwidth of 1GHz at 6GHz center frequency. The distance between each element and the EBG ground plane was $0.06\lambda_0$. Another study proposed a low-profile single-arm squared spiral antenna over a mushroom like EBG structure for wireless communications [17]. At a distance of $0.06\lambda_0$, between the antenna and the EBG ground plane, fairly good circularly polarized radiation pattern was achieved. The EBG ground plane of this study had a planar size of $0.82\lambda_0 \times 0.82\lambda_0$, with an array of 6×6 square patches etched on a grounded dielectric slab. All of these structures have used array patches with a vertical via.

In this thesis, single and dual arm spiral antennas are investigated over an artificial magnetic conductor (AMC) ground plane for low profile applications. AMC structures are high impedance surfaces that may support surface waves. The spiral antenna generates circularly polarized waves. The minimum distance of $0.02\lambda_0$ is obtained by using patch arrays as small as 4×4 square patches, in the AMC ground plane without shorting pins (vias). The operating frequency is 4.5GHz. To have a physically robust structure, the spiral antenna is printed on a dielectric slab, which is placed over the AMC ground plane. Comprehensive parametric studies are carried out to understand their effects on the antenna performance. The proposed design may be practically applied in global positioning systems (GPS), local area networks (LAN), and wireless communications.

1.3 Organization of the Thesis

The thesis is presented in seven chapters. Chapter one covers introduction and literature review on the topic and describes its overall goals. Chapter two gives the background theory on Archimedean spiral antennas and artificial magnetic conductors

(AMC). It is explained how the spiral antenna radiates at its fundamental mode in the active region. This region is where the circumference of the spiral antenna is approximately one wavelength. The high-impedance AMC structure, having a zero reflection phase, allows situating the planar antenna very close to the artificial ground plane. The investigation of curl antennas over an infinite PEC ground plane is given in chapter three. It is shown that a minimum distance of a quarter-wavelength is needed to have a good circular polarization performance. Chapter four covers low-profile curl antennas over an AMC ground plane consisting of squared patches without vias. Different parametric studies are performed in terms of curl specifications, different number of AMC patches, and feeding position. The optimum low-profile curl antenna, found in chapter four, is manufactured and the experimental results are given in chapter five. It is shown that there is a good agreement between simulation and measurement results. In chapter six, a dual-arm Archimedean spiral antenna is studied over both PEC and AMC ground planes. Excellent symmetric patterns are obtained by the dual arm spiral antenna. Finally, the conclusion and future work are given in chapter seven.

Chapter 2

Basic Theories of Spiral Antennas and AMC

Structures

2.1 Introduction

It is known that the antenna characteristics such as impedance, radiation patterns, and polarization, remain unchanged when its physical size and operating frequency are inversely scaled. That is, for antennas constructed with perfect conductors, the operating frequency will be scaled by a factor of $1/n$ if the physical dimensions of the antenna are scaled by a factor of n . However, as Victor Rumsey showed in 1957 [5], the performance of an antenna will be independent of frequency if its geometry is completely defined by angles rather than lengths.

In this chapter, Archimedean spiral antennas and Artificial Magnetic Conductor (AMC) structures will be reviewed. This type of antennas is in the class of frequency independent antennas, and generates circularly polarized waves. When it is backed by a traditional ground plane, the minimum required height is a quarter-wavelength which is a main restriction in low profile applications. To overcome this problem, an AMC ground plane can be used.

2.2 Basic Theory of Archimedean Spiral Antenna

Spiral antennas can be categorized as frequency-independent antennas. According to [6, 21], the radiation patterns of practical frequency-independent antennas have a bandwidth of about 10:1 or more. The geometry of frequency-independent antennas, based on Rumsey's principle [5], is defined only by angles rather than length. Also, frequency-independent antennas are self-complementary structures. Self-complementary antennas, first discovered by Mushiake in 1948 [19], have constant impedance of $\eta/2$ or 188.5 ohms, where η is the characteristic impedance of the free space [5, 18]. For instance, a planar two-arm Archimedean spiral antenna, in which the width of each arm is equal to the spacing between each turn, is a self-complementary structure as shown in Fig.2.1. In order for the antenna structure to be self-complementary an infinitesimally thin planar and perfectly conducting shape of infinite extend are needed [20].

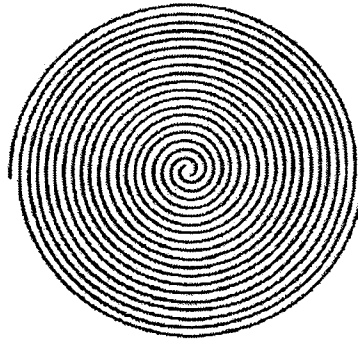


Fig. 2.1: Geometry of Two-arm Archimedean Spiral [21]

The infinite geometry concept is a theoretical idea which cannot be implemented in practical applications. However, there is a way to implement the frequency independent antenna using a finite structure by truncating the structure at the point where the current attenuates and goes to zero. As a consequence of achieving the frequency independent

antenna in a finite structure, the lower bound of the frequency will be limited, while the radiation properties of the antenna will remain nearly unchanged over a wide range of frequencies. In the curved structures such as the spirals, most radiation occurs where the circumference of the antenna is one wavelength. This portion is usually known as the active region [21].

The equation of Archimedean spiral curve, shown in Fig. 2.2, in polar coordinates is given by

$$r = a\alpha + r_o \quad (2.1)$$

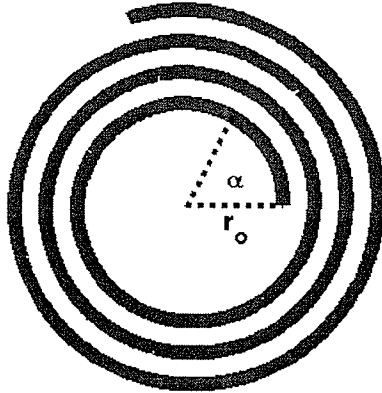


Fig. 2.2: Geometry of Single-arm Archimedean Spiral.

where r_o and r are the radial distances from the origin at the angles (in radians) $\alpha = 0$ and “ a ”(mm/rad) is the spiral constant showing the flare rate of the spiral. Therefore, a smaller value for “ a ” will result in a slower flare rate. The turning direction of the spiral is right-handed, or counterclockwise, if “ a ” is positive and left-handed, or clockwise, if “ a ” is negative. An antenna, defined by Eq. (2.1), can be easily fabricated using printed circuit board (PCB) techniques. As previously mentioned, the spiral antenna radiates most of its energy inside the active region. Thus, for a finite antenna structure surrounded by the free space, the lower- and upper-bound frequencies are limited, respectively as

$$\lambda_{lower-bound} \cong 2\pi r_{out} \Rightarrow f_{lower-bound} = \frac{c}{2\pi r_{out}} \quad (2.2a)$$

$$\lambda_{upper-bound} \cong 2\pi r_{in} \Rightarrow f_{upper-bound} = \frac{c}{2\pi r_{in}} \quad (2.2b)$$

where r_{in} and r_{out} are the inner and outer radii, $\lambda_{lower-bound}$ and $\lambda_{upper-bound}$ are the lowest and highest operating wavelengths, and c is the speed of light in free space. Equations (2.2) are valid when the space between the neighboring wires is much smaller than r , the spiral radius [22].

In the active region, currents of the points that are a quarter-wavelength apart along the arm of the spiral have a 90 degree phase difference electrically but have equal amplitudes. Furthermore, the current of these points are perpendicular in space. These conditions make the spiral antenna to radiate circular polarization, with the sense of polarization corresponding to the sense of spiral winding. The polarization sense of the radiated wave is right-handed if the sense of spiral winding is right-handed and vice versa [21].

Planar spiral antennas radiate bi-directionally. However, in most applications, a uni-directional pattern is desired [23]. To obtain a uni-directional pattern, one may use either a plane of perfect electric conductor or a lossy cavity with an electromagnetic wave absorber.

In the spirals backed by a lossy cavity, half of the radiated power is dissipated inside the absorber and the other half is radiated in the opposite direction. By using such a combination, a wide band structure is achieved, at the expense of diminished 3dB power [24]. According to [25], in order to improve the frequency bandwidth, cavity depth must

be larger than the spiral radius. Thus, the addition of the cavity makes the antenna large and bulky.

Another solution is to place the spiral over a conducting planar reflector. A comprehensive study of using a conducting planar reflector has been performed by Nakano [24-25]. It has been indicated that when a conducting planar reflector is located in the back of spiral at a distance smaller than a quarter-wavelength, it causes an undesired interference with the desired radiation [25]. As a result, the antenna axial ratio deteriorates in the boresight direction. Thus, the minimum distance between the spiral and the plane of perfect electric conductor is limited to a quarter-wavelength [26], resulting in another combination that is bulky.

Thus far, a cavity-backed planar spiral and conducting planar reflector are not acceptable candidates for low-profile antennas.

2.3 Basic Theory of AMC

The ground plane plays an important role in the antenna design in wireless communications. A perfect electric conductor (PEC), which has been traditionally used as a ground plane, has some deficiencies in low profile antenna applications. That is, it reverses the phase of the reflected wave when the antenna is very close to a PEC ground plane. Furthermore, with grounded dielectrics, it generates surface waves, which in turn result in low antenna efficiency. Instead of a PEC, a perfect magnetic conductor (PMC) may serve as a potential candidate for a ground plane. It is the electromagnetic dual of a PEC, but does not exist in nature. A PMC can circumvent the above mentioned restrictions by having an in-phase reflected wave current for small heights, as depicted in Fig. 2.3, and suppressing the normally polarized surface waves [28].

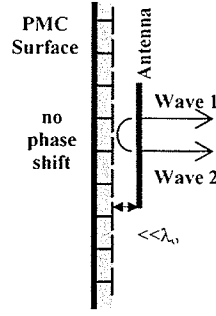


Fig. 2.3: Illustration of the in-phase reflected wave by PMC ground plane in the proximity of a planar antenna [29]

In electromagnetic theory, both electric and magnetic fields are zero inside a perfect magnetic conductor. Using the principle of duality, the tangential components of the magnetic field are zero on its surface. The boundary conditions are given below, with the assumption that medium 1 is a perfect magnetic conductor ($H_{1t}=0$) [27].

$$-\hat{n} \times \vec{E}_2 = \vec{M}_s \quad (2.3a)$$

$$\hat{n} \times \vec{H}_2 = 0 \quad (2.3b)$$

$$\hat{n} \cdot \vec{D}_2 = 0 \quad (2.3c)$$

$$\hat{n} \cdot \vec{B}_2 = q_{ms} \quad (2.3d)$$

where M_s and q_{ms} are magnetic current and surface charge density, respectively.

The surface impedance is defined as the ratio of the tangential electric field to the tangential magnetic field. At a PEC surface, which has a boundary condition of zero tangential electric field, the surface impedance is zero for all angles of incidence. Therefore, the plane wave reflection coefficient for a PEC is -1. While at a PMC surface, the boundary condition of $H_{tan}=0$ provides an infinite surface impedance. Consequently, the plane wave reflection coefficient is +1 for all angles of incidence.

As mentioned earlier, a perfect magnetic conductor does not physically exist in nature. However, their properties can be artificially engineered using periodic dielectric substrates and metallization patterns. Such periodic structures are called artificial magnetic conductors (AMC). As shown in Fig. 2.4, the mushroom-like high impedance surface developed by Sievenpiper [1, 29] serves as an example of AMC structures. This surface consists of an array of metallic patches backed by a grounded dielectric slab. Each patch is shorted to the metallic sheet using vias. When the periodicity of each patch is much less than the wavelength, they can be modeled using lump elements, an LC resonant circuit. At the resonant frequency, this structure provides a zero tangential magnetic field, acting like a high-impedance surface. As a result, the reflection phase will be zero. The AMC's may have also a surface wave band-gap, within which they can suppress either transverse magnetic (TM) or transverse electric (TE) surface waves. They are classified as Electromagnetic Band-Gap (EBG) structures as described in further detail in [30, 31].

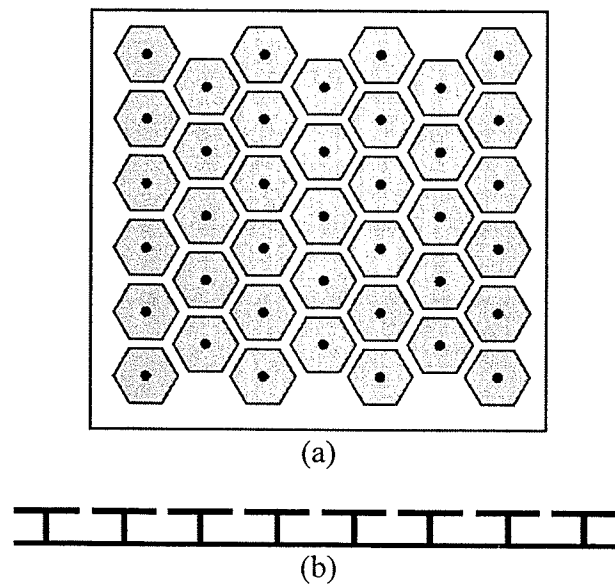


Fig. 2.4: (a) Top view and (b) Cross-section of a high-impedance surface [29]

A typical behavior of EBG reflection phase is illustrated in Fig. 2.5. As shown, there exists only one point where the reflected wave experiences a zero phase. However, the frequency range where the reflection phase is within ± 90 degrees is conventionally defined as a bandwidth of the PMC-like behavior.

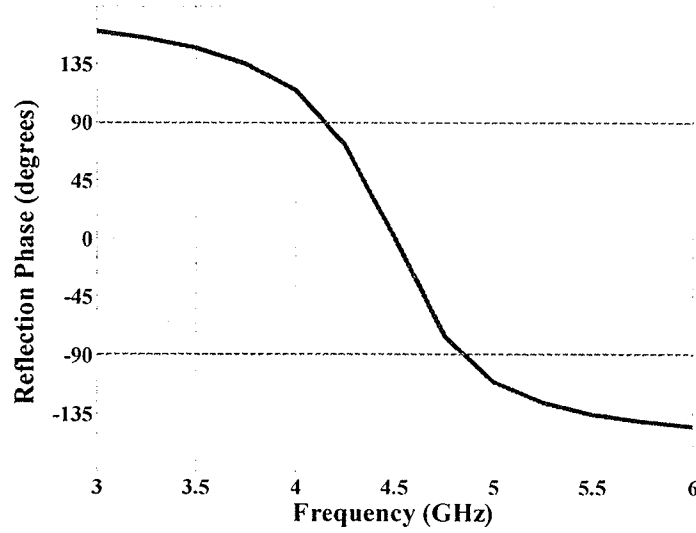


Fig. 2.5: Reflection phase for normally incident plane wave for AMC structure

In the present study, the AMC surfaces are developed using square patches without shorting vias. The new AMC surfaces are, thus, made of only patches to simplify the fabrication process. Removing vias has a negligible impact on the reflection phase for normal incident plane waves. However, if not designed properly the structure can support surface waves [32]. The investigation of low-profile dipole antenna over an AMC without vias is reported in [33-35]. The geometry of this structure is depicted in Fig. 2.6. It consists of a grounded dielectric slab loaded with periodic square patches with no vertical vias.

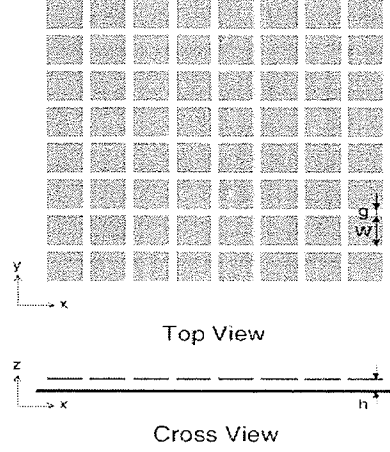


Fig. 2.6: Top and Cross views of an AMC with no vias [35]

2.4 Design of an AMC Structures with no Vertical Vias

The following is a description of the design procedure of a unit cell in an AMC structure fabricated without vias. The geometry of the unit cell is shown in Fig. 2.7. As mentioned earlier, when the periodicity is much less than the wavelength, the structure can be analyzed using lumped-element circuit parameters that are determined by the geometry of the surface. For this case, the equivalent model is a parallel LC circuit. The shunt capacitor C takes into account the interaction between two adjacent square patches. Using the transmission line model, parallel inductor L may represent a segment of a shorted transmission line with a length equal to the dielectric thickness “ h ”. The equivalent impedance of the surface can easily be given by [34] as

$$Z_{LC} = j \frac{X_L X_C}{X_C - X_L} \quad (2.4)$$

where,

$$X_L = \frac{\eta_0}{\sqrt{\epsilon_r}} \tan(k_0 \sqrt{\epsilon_r} h) \quad (2.5)$$

$$X_C = \frac{1}{\omega C} \quad (2.6)$$

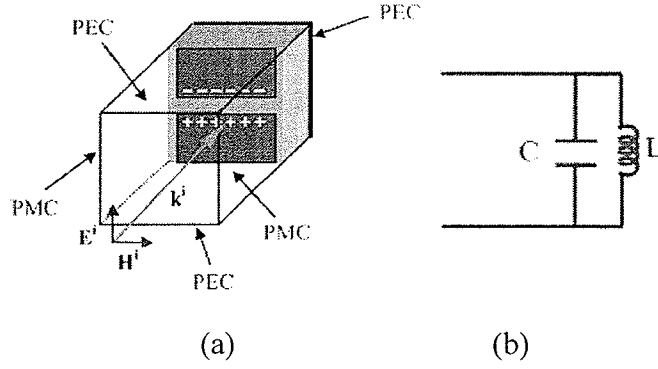


Fig. 2.7: (a) Unit cell of the AMC shown in Fig. 2.6, illuminated by the normal incident plane wave. (b) Parallel LC equivalent model [34].

The capacitance per unit length of two coplanar strips, as shown in Fig. 2.8, can be approximately calculated from the following equation [36-37].

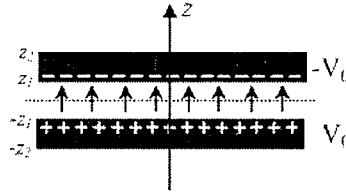


Fig. 2.8: Representation of the shunt capacitor in the unit cell shown in Fig. 2.7 [34].

$$C_0 = \frac{\varepsilon K\left(\sqrt{1 - (z_1/z_2)^2}\right)}{K(z_1/z_2)} \quad (2.7)$$

where $K(z)$ represents the complete elliptic integral defined by

$$K(z) = \int_0^{\pi/2} \frac{d\phi}{\sqrt{1 - z^2 \sin^2 \phi}} \quad (2.8)$$

Parameters z_1 and z_2 are shown in Fig. 2.8. The capacitor C can be easily found by multiplying C_0 by the effective length of the square patch. The above formulas are valid

for normal incidence plane waves. Equations for oblique incident waves can be found in [34].

From Eq. 2.4 it is clear that the surface has infinite impedance at the resonant frequency. Therefore, it behaves as a PMC structure providing an in-phase reflected wave.

It was observed that the resonant frequency obtained from the above equations had a small discrepancy with the one obtained by Finite Element based software the HFSS v10.1. In order to match simulated results with calculated ones, a correction factor of about 0.82 needs to be multiplied by the resonant frequency. The final tuning is carried out by software.

2.5 Proposed Study

In this thesis, two Archimedean spiral antennas will be studied over an AMC ground plane without vertical via. The main goal is to develop a low-profile antenna with good circularly polarized behavior, that is, the axial ratio of less than 3 dB over desired observation angles. The first study is a single-arm curl antenna as shown in Fig. 2.9. According to [38, 39], the simplest configuration of an Archimedean spiral antenna is called a curl antenna. It comprises a single turn Archimedean spiral, radial linear, and the vertical feed probe sections. The radial linear section of this antenna is just for the feeding purpose and does not have a significant impact on the radiation when the antenna is backed by a PEC ground plane [40].

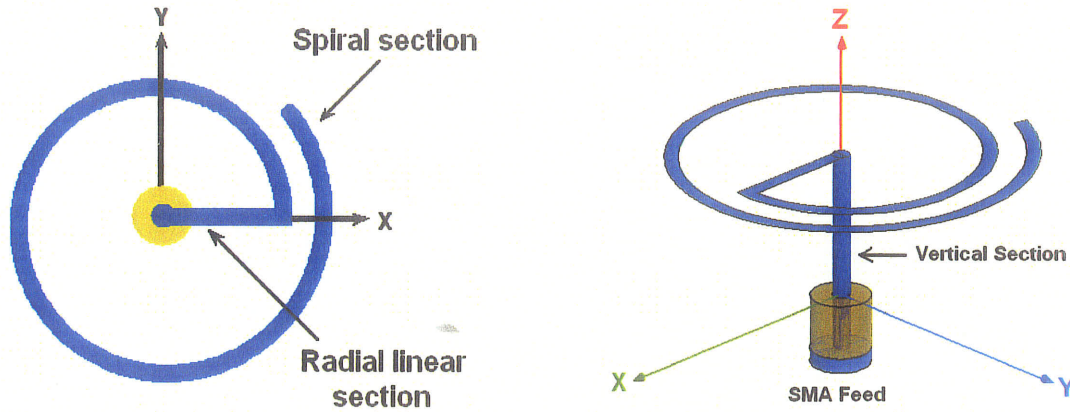


Fig. 2.9: Geometry of Curl antenna with its three main sections

Different parametric studies will be completed in terms of the spiral height, the number of turns, and the spiral constant. It will be shown that a curl antenna can be situated over an AMC ground plane at a small distance of $0.02\lambda_0$ to construct a low-profile antenna with a good circular polarization, which is in good demand in wireless communication systems.

The second study will further examine a dual-arm spiral antenna. Similarly, the effect of different parameters on the axial ratio will be investigated over the same AMC ground plane as above with no via. To have a physically robust structure, both antennas will be printed on a dielectric slab, which will be placed over the AMC ground plane.

2.6 Summary

In this chapter, basic theories of Archimedean spiral antenna, EBG structure, and AMC ground plane were briefly reviewed. The design procedure for the antenna and artificial ground plane were formulated. The main purpose of the thesis is to develop a low-profile antenna producing circularly polarized waves with good axial ratio over an

AMC ground plane without vias. This class of antenna will have broad applications in wireless communication systems.

Chapter 3

Curl Antenna over PEC Ground Plane

3.1 Introduction

This chapter studies a curl antenna over an infinite PEC ground plane. Curl antennas, similar to spiral antennas, generate circularly polarized waves. It is shown how changing the curl parameters affects its axial ratio. The curl parameters include the number of turns “n”, the curl height “h” (the distance between the curl and ground plane), and the curl constant “a”. For instance, decreasing the distance between the curl antenna and the PEC ground plane to less than $\lambda_0/4$ (the free space wavelength) deteriorates its axial ratio. Simulations are carried out by the HFSS v10.1 based on the Finite Element method. The operating frequency is 4.5GHz ($\lambda_0 = 66.67\text{mm}$).

3.2 Effect of Height on Axial Ratio (AR)

Axial ratio is the quality of circular polarization of the wave and it is expressed by the following equation for the left-hand and right-hand circularly polarized waves, LHCP and RHCP, respectively [27]:

$$AR(dB) = 20 \log \frac{|E_L| + |E_R|}{|E_L| - |E_R|} \quad \text{LHCP} \quad (3.1a)$$

$$AR(dB) = 20 \log \frac{|E_R| + |E_L|}{|E_R| - |E_L|} \quad \text{RHCP} \quad (3.1b)$$

where E_L and E_R are the left-hand and right-hand polarization components, respectively, and they are calculated by

$$E_L = (E_\theta - jE_\phi)/\sqrt{2} \quad (3.2a)$$

$$E_R = (E_\theta + jE_\phi)/\sqrt{2} \quad (3.2b)$$

The far-field electric field is specified by θ and ϕ components in spherical coordinates as follow:

$$\vec{E} = E_\theta \hat{a}_\theta + E_\phi \hat{a}_\phi \quad (3.3)$$

where E_θ and E_ϕ are phasor components in the direction of the unit vectors $\hat{a}_\theta$ and $\hat{a}_\phi$.

3.2.1 Design optimization

As mentioned in chapter 2, the curl antenna radiates when the circumference of the antenna is approximately one wavelength. For small values of curl constant “a”, i.e. slower flare rate, the circumference of the curl is approximately equivalent to that of a circle with the radius of $r = a \alpha_{st}$. Therefore, the circumference will be equal to $2\pi r$. Given the center operating frequency of 4.5GHz and the bandwidth of 1GHz, $f_{upper-bound} = 5\text{GHz}$ and $f_{lower-bound} = 4\text{GHz}$. Substituting values of $f_{upper-bound}$, $f_{lower-bound}$ and λ_0 into Eq.2.2, the parameters defining the curl antenna can be calculated as the initial design values. These values were optimized by full wave analysis method like the HFSS v10.1. The geometry of the antenna is shown in Fig. 3.1, and the results are given in Table 3.1, where $n = \alpha_{end} / \alpha_{st}$.

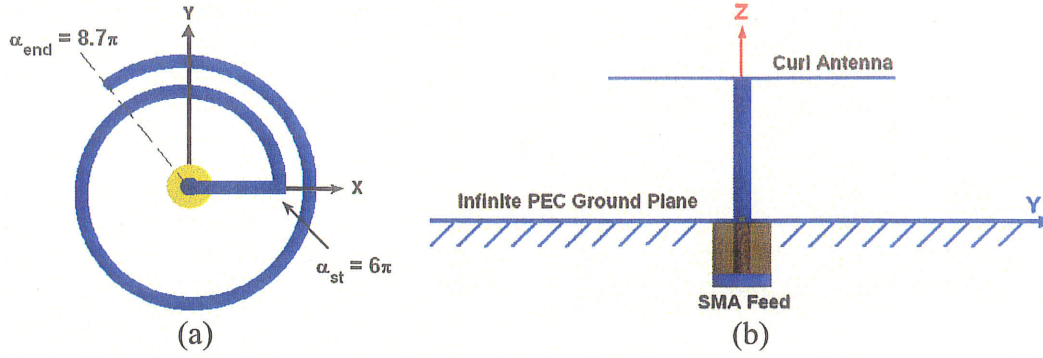


Fig. 3.1: (a) Top view and (b) side view of the curl antenna over an infinite PEC ground plane.

Table 3.1: Optimized values of the curl antenna shown in Fig.3.1 over an infinite PEC ground plane.

Curl constant “a” (mm/rad)	0.485
Number of turns “n”	1.45
$\alpha_{st}(\text{radians})$	6π
Height “h” (mm)	$16.67=\lambda_0/4$

As mentioned earlier, the curl antenna is the simplest configuration of an Archimedean spiral antenna. Thus, the design parameters for the curl are the same as those for the Archimedean spiral. As shown in Fig.3.1, the curl antenna consists of two parts: the radial and spiral sections. The radial section is to facilitate the feeding. When the curl antenna is placed over an infinite PEC ground plane, the radial section has no significant effect on the circular polarization performance of the antenna [40]. The spiral part produces right-hand circularly polarized (RHCP) waves as explained in chapter two. This antenna is simulated over an infinite PEC ground plane using the HFSS v10.1 software that is based on the Finite Element method.

3.2.2 Effect of Height on AR

Changing the distance between the curl antenna and infinite ground plane can affect the axial ratio. This effect is shown in Fig. 3.2 at $\theta=0^\circ$. It should be mentioned that the curl constant and the number of turns are kept unchanged as $a=0.485\text{mm/rad}$ and $n=1.45$. As observed in Fig. 3.2, the minimum axial ratio is obtained at the center operating frequency of 4.5GHz when “h” is equal to 16.67 mm, which is equal to the expected value of a quarter-wavelength. This optimum distance of $\lambda_o/4$ can be explained by modeling the antenna and its ground plane using a transmission line. The wave, traveling from the antenna toward the ground plane, will have a 90° phase shift as demonstrated in Eq.3.4.

$$kh = \frac{2\pi}{\lambda} \times \frac{\lambda}{4} = \frac{\pi}{2} \quad (3.4)$$

The ground plane itself has a negative reflection coefficient, $\Gamma = -1$, corresponding to an 180° phase shift. The reflected wave will travel back the same distance of $\lambda_o/4$, which again experiences another 90° phase shift. Therefore, the overall phase shift will be $\pi/2 + \pi + \pi/2 = 2\pi$. Consequently, the far-field radiation pattern of the antenna will be optimized for the best circular polarization performance. Thus, when the distance is not $\lambda_o/4$ the radiation pattern degrades resulting in a poor axial ratio. It follows that when the overall phase shift is $2n\pi$, the same results will be obtained. However, these distances are not proper choice for low-profile applications.

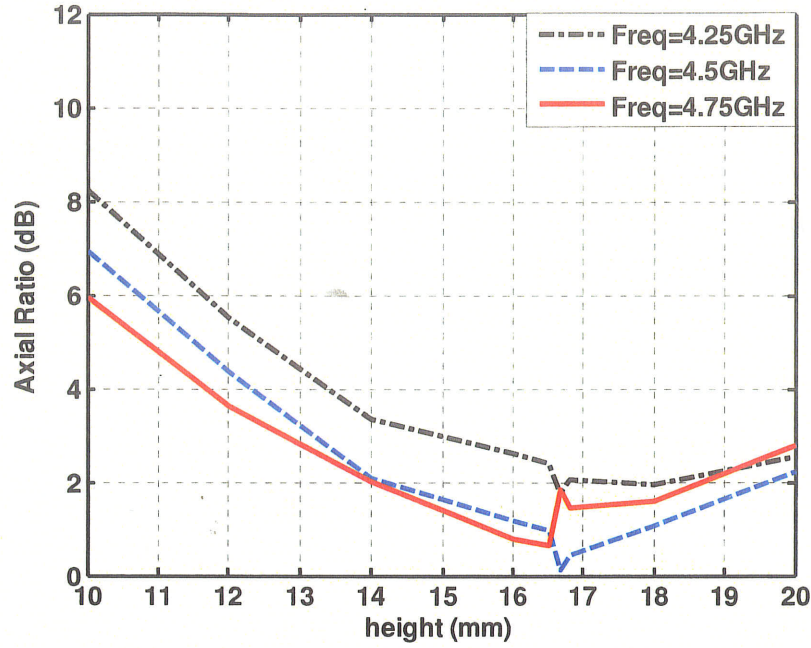


Fig. 3.2: Axial ratios of the antenna shown in Fig.3.1 versus height at $\theta=0^\circ$, when $a=0.485\text{mm/rad}$, $n=1.45$, at $f = 4.25\text{GHz}$, 4.5GHz , and 4.75GHz .

Figure 3.3 illustrates the axial ratio over observation angles for different heights at ϕ equal to 0° , 45° , 90° , and 135° planes. The remaining curl parameters kept unchanged as $n=1.45$ and $a=0.485\text{mm/rad}$. Again, the best circular polarization is observed when the distance of the planar curl antenna and the ground plane is a quarter-wavelength. The observed distance is the same height reported in [38] for a curl antenna over a PEC ground plane. As observed in Fig.3.3, another local minimum occurs around $\theta=70^\circ$, due to the interaction between the radiation patterns of the radial linear and vertical sections. This local minimum reaches to 1dB at $\phi=90^\circ$, where the interaction between the two orthogonal sections is maximum.

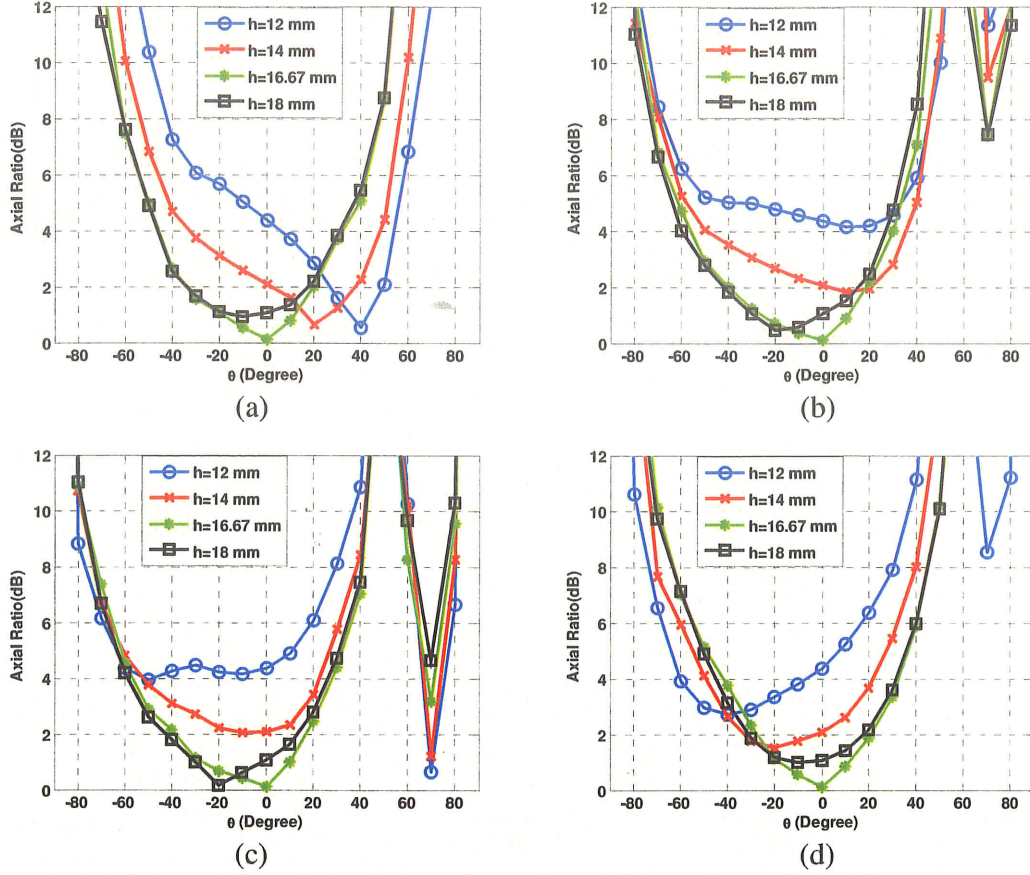


Fig. 3.3: Axial ratios of the antenna shown in Fig.3.1 for different heights, when $a=0.485\text{mm/rad}$, $n=1.45$, and $f=4.5\text{GHz}$, at (a) $\phi=0^\circ$ plane (b) at $\phi=45^\circ$ plane (c) $\phi=90^\circ$ plane (d) $\phi=135^\circ$ plane.

3.3 Effect of Number of Turns on Axial Ratio (AR)

In this section, the effect of the number of turns “ n ” on the axial ratio of the antenna shown in Fig. 3.1 is studied. The distance between the curl antenna and PEC ground plane remains constant at $\lambda_o/4$. This is because of the fact that the antenna height of $\lambda_o/4$ provides the best circular polarization performance based on preceding section. Similar to the previous section, the curl constant is equal to 0.485 mm/rad . The relationship between the axial ratio and the number of turns is shown in Fig. 3.4 at the boresight direction

$\theta=0^\circ$. As observed in this figure, the minimum axial ratio occurs at the center operating frequency of 4.5GHz when “n” is equal to 1.45. This is where the circumference of the curl antenna is approximately one wavelength. Therefore, the antenna is within its active region.

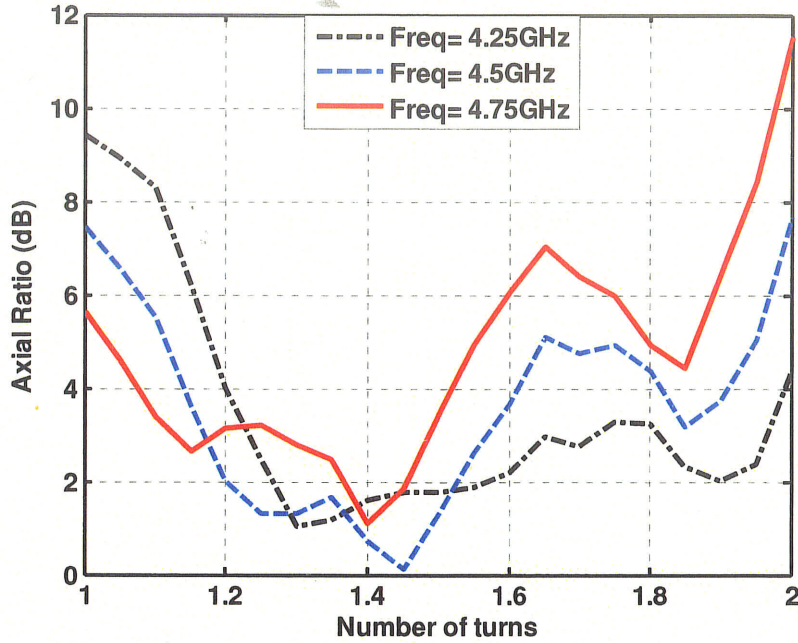


Fig. 3.4: Axial ratios of the antenna shown in Fig.3.1 versus number of turns at $\theta=0^\circ$, when $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$, at $f = 4.25\text{GHz}$, 4.5GHz , and 4.75GHz .

Figure 3.5 depicts that the axial ratio over observation angles for different numbers of turns at ϕ equal to 0° , 45° , 90° , and 135° planes. The other curl parameters remain unchanged as $h=16.67\text{mm}$ and $a=0.485\text{mm/rad}$. Results of four different numbers of turns are given. These numbers are $n=1.1$, 1.2 , 1.45 , 1.6 turns. The case of $n=1.45$ has the best axial ratio at all ϕ planes among the simulated cases. All cases, but $n=1.45$ turns, are asymmetric over observation angles. For example, the case of $n=1.1$ turns has an axial

ratio that is more than 3dB over the boresight angle at ϕ equal to 45° and 90° as shown in Figs.3.5b and c.

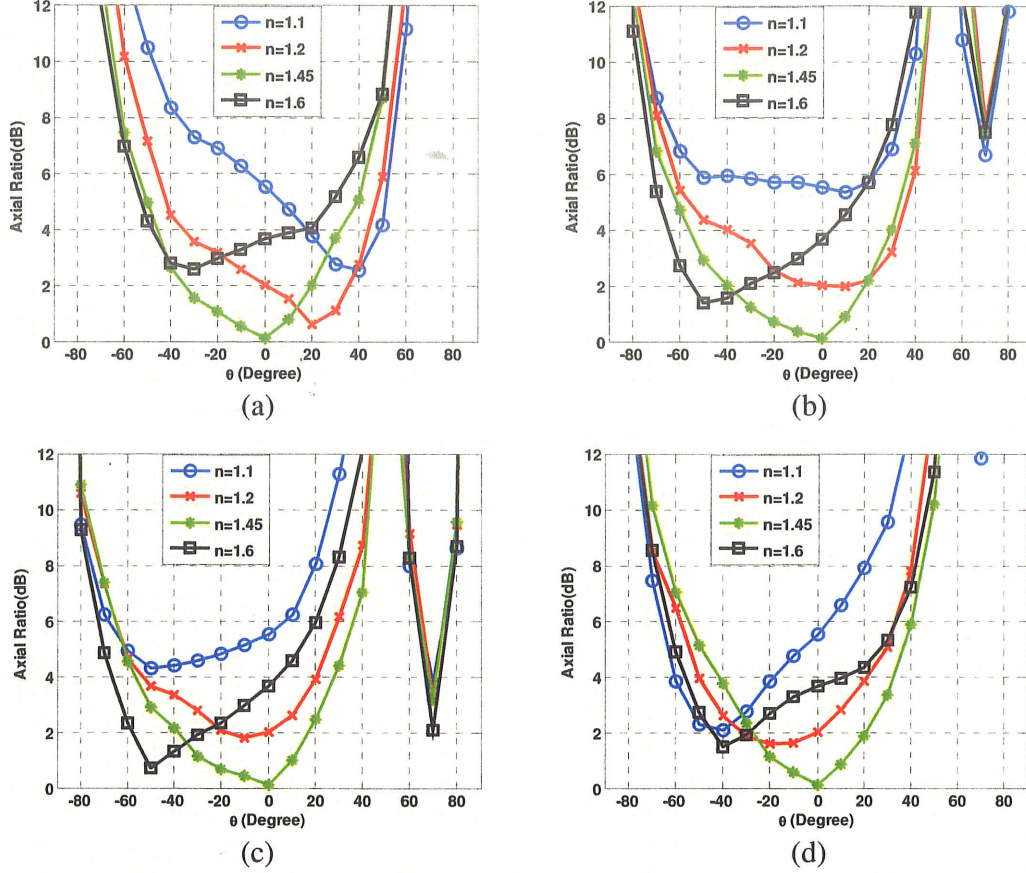


Fig. 3.5: Axial ratios of the antenna shown in Fig.3.1 for different number of turns, when $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$, and $f=4.5\text{GHz}$, at $\phi=0^\circ$ plane (b) at $\phi=45^\circ$ plane (c) $\phi=90^\circ$ plane (d) $\phi=135^\circ$ plane.

3.4 Effect of Curl Constant on Axial Ratio (AR)

The last parametric study is the impact of the curl constant “a” on the axial ratio of the curl antenna over an infinite PEC ground plane. For this study, the height of the antenna is constant and selected as $\lambda_0/4$. Moreover, the number of turns is kept constant and equal to 1.45, as determined in section 3.3. The curl constant cannot deviate

significantly from the designed value of 0.485mm/rad since it will drastically change the frequency behavior of the curl antenna. Therefore, the results for four very close values of “a” are presented in this section. Those curl constants are: 0.475, 0.480, 0.485, and 0.490mm/rad. Figure 3.6 illustrates how the curl constant affects the axial ratio over observation angle at different ϕ -planes. As can be seen, the axial ratio of the curl antenna is less than 3dB over the observation angles of $-45^\circ \leq \theta \leq +30^\circ$. Table 3.2 gives the axial ratio at $\theta=0^\circ$ for the above mentioned curl constants.

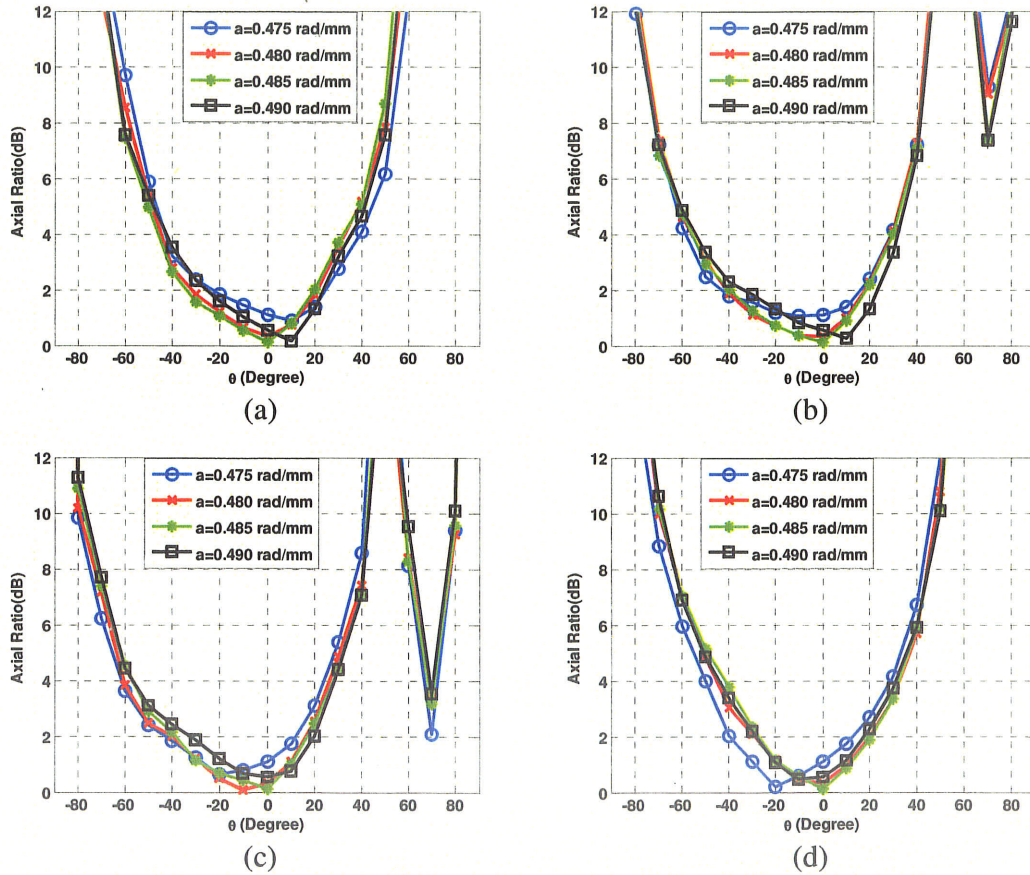


Fig. 3.6: Axial ratios of the antenna shown in Fig.3.1 for different curl constants, when $h=16.67\text{mm}=\lambda_0/4$, $n=1.45$, and $f=4.5\text{GHz}$, at (a) $\phi=0^\circ$ plane (b) at $\phi=45^\circ$ plane (c) $\phi=90^\circ$ plane (d) $\phi=135^\circ$ plane.

Table 3.2: Axial ratios of the antenna shown in Fig. 3.1 versus different curl constants at $\theta=0^\circ$ when $h=16.67\text{mm}=\lambda_0/4$, $n=1.45$, at $f = 4.25\text{GHz}$, 4.5GHz , and 4.75GHz .

Curl constant “a”(mm/rad)	AR(dB) 4.25GHz	AR(dB)@4.5GHz	AR(dB)@4.75GHz
0.475	2.65	1.0995	0.62
0.480	1.97	0.3442	1.68
0.485	1.78	0.1100	1.86
0.490	1.95	0.5324	1.41

From the parametric studies of a curl antenna over an infinite PEC ground plane, it is concluded that the optimum circular polarization occurs when $n=1.45$ turns, $a=0.485\text{mm/rad}$, and $h=16.67\text{mm}=\lambda_0/4$ at the center operating frequency of 4.5GHz . Therefore, the antenna height of $\lambda_0/4$, at the center operating frequency of 4.5GHz , is required to obtain the optimum circular polarization performance. The axial ratio for the above mentioned case is shown in Fig.3.7 at different ϕ -planes. As can be seen, the axial ratio of almost 0dB is obtained at $\theta=0^\circ$ and it is less than 3dB over the observation angles of $-35^\circ \leq \theta \leq +25^\circ$. However, slightly asymmetric behavior near the endfire direction is observed, as a result of the asymmetric geometry of the curl antenna itself. As explained in section 2.2, the proposed curl antenna is the right-handed circularly polarized. To show the frequency behavior of the above optimum case, Fig. 3.8 depicts the axial ratios at two different frequencies of 4.25GHz and 4.75GHz . The overall CP performance is still acceptable although the minimum axial ratio is shifted off the boresight direction. Figure 3.9 shows the right hand and left hand circular polarized gains of the optimum curl antenna over an infinite ground plane at principal planes. Maximum right-hand, or the copolarized, gain of 7.5dBic is obtained at the boresight angle. The left

handed wave, or the cross polarization, is about 25dB below the copolarized one near $\theta = 0^\circ$. Also, Fig.3.10 illustrates the right-hand and left-hand circular gain patterns at two different frequencies of 4.25GHz and 4.75GHz. The RHCP gain is almost unchanged. Fig. 3.11 shows the normalized CP radiation patterns at different ϕ -planes and $f=4.5$ GHz. As can be seen, the right handed CP wave is dominant at all ϕ -planes.

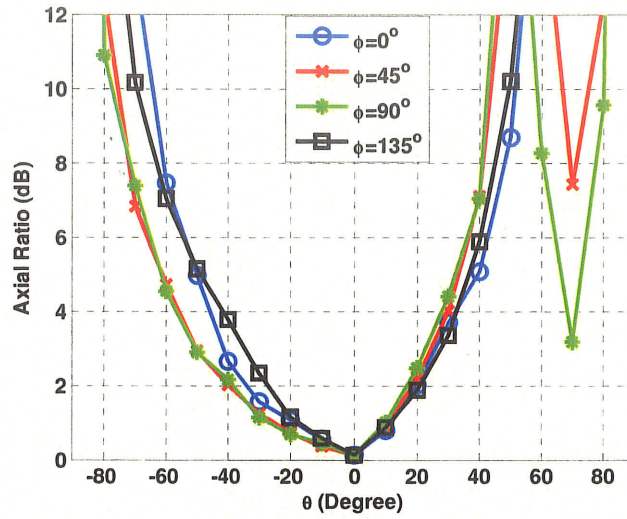


Fig3.7: Axial ratios of the antenna shown in Fig.3.1 for the optimum case ($n=1.45$ turns, $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$ and $f=4.5\text{GHz}$) at $\phi=0^\circ$, 45° , 90° , and 135° planes.

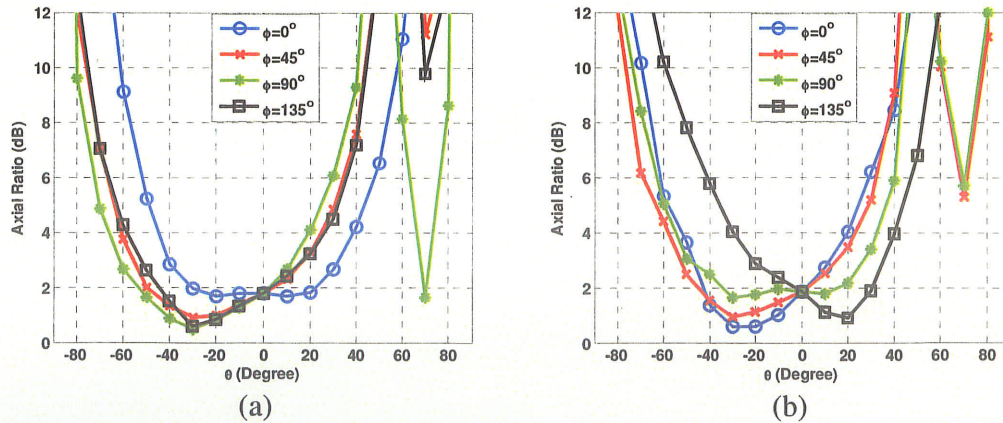


Fig. 3.8: Axial ratios of the antenna shown in Fig. 3.1 for the optimum case ($n=1.45$ turns, $a=0.485\text{mm/rad}$, and $h=16.67\text{mm}=\lambda_0/4$) at $\phi=0^\circ$ and 90° planes and (a) $f=4.25\text{GHz}$ (b) $f=4.75\text{GHz}$.

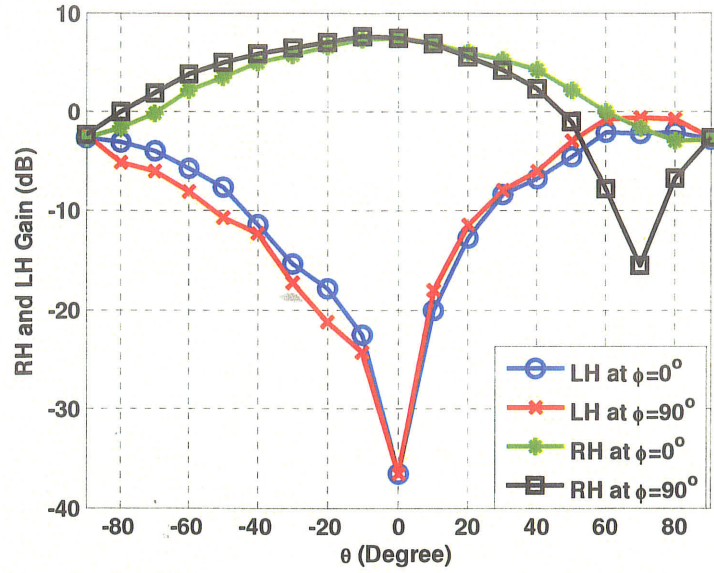


Fig3.9: Right-Hand and Left-Hand gains of the antenna shown in Fig.3.1 for the optimum case ($n=1.45$ turns, $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$, and $f=4.5\text{GHz}$) at $\phi=0^\circ$ and 90° planes.

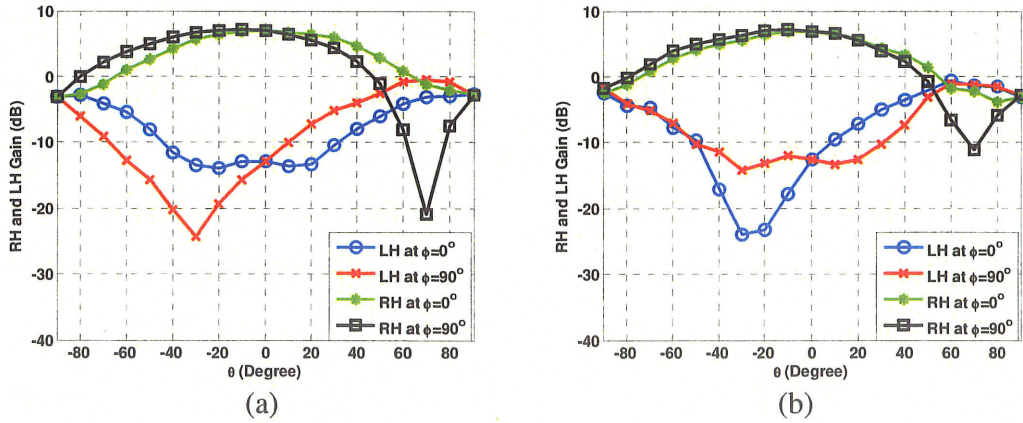


Fig. 3.10: Right-Hand and Left-Hand, copular and cross polar, gains of the antenna shown in Fig. 3.1 for the optimum case ($n=1.45$ turns, $a=0.485\text{mm/rad}$, and $h=16.67\text{mm}=\lambda_0/4$) at $\phi=0^\circ$ and 90° planes and (a) $f=4.25\text{GHz}$ (b) $f=4.75\text{GHz}$.

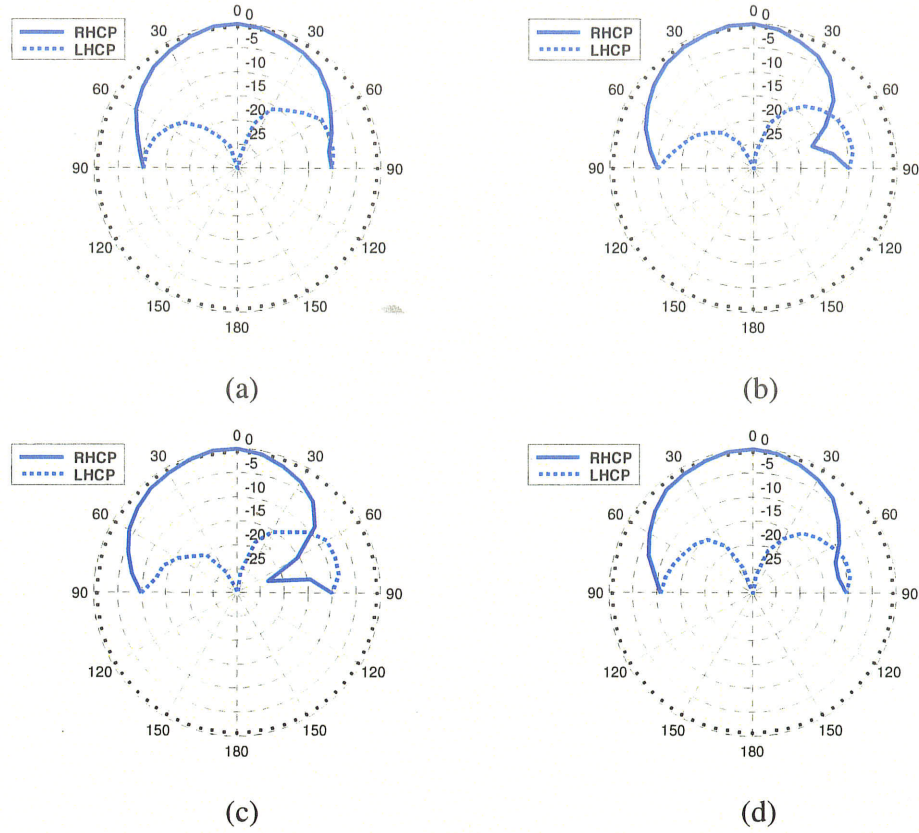
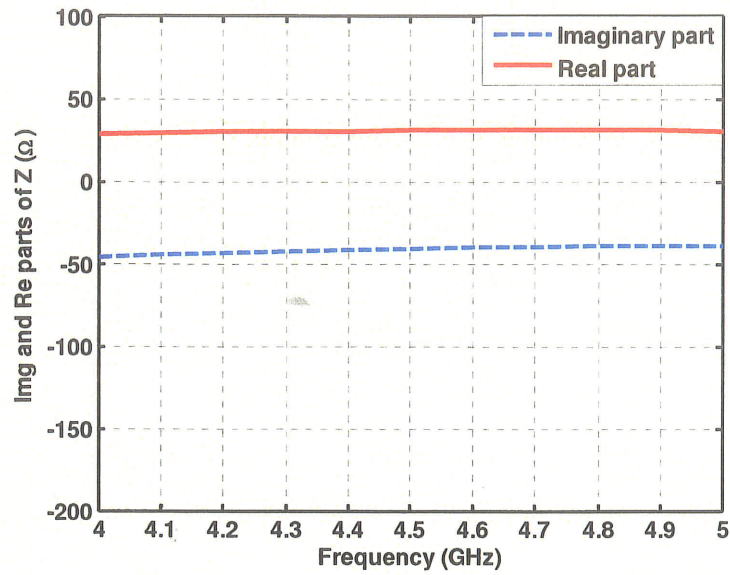
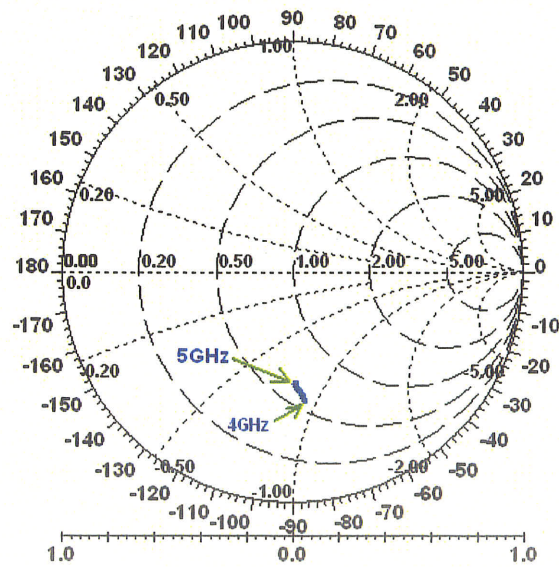


Fig. 3.11: Normalized radiation patterns of the antenna shown in Fig.3.1 with optimized parameters $n=1.45$, $a=0.485$ mm/rad, and $h=16.67$ mm $=\lambda_0/4$, for different ϕ planes :(a) $\phi=0^\circ$ (b) $\phi=45^\circ$ (c) $\phi=90^\circ$ (d) $\phi=135^\circ$ at $f=4.5$ GHz.

The real and imaginary parts of the input impedance of the optimum curl antenna are shown in Fig.3.12a over the frequency range of 4.0GHz to 5.0GHz. The real part is almost constant in this frequency range and it is equal to 30Ω . The negative imaginary part describes the capacitive behavior of the input impedance over the frequency range. As both real and imaginary parts do not change over the frequency range of 4.0GHz to 5.0GHz, the antenna can be easily matched, in practice, to a constant impedance of a like 50Ω system. Also, the Smith chart of the input impedance is given in Fig. 3.12b. This also confirms that the input impedance is almost constant over the operating frequency bandwidth.



(a)



(b)

Fig. 3.12: (a) Real and Imaginary parts (b) Smith chart of the input impedance for antenna of Fig.3.1, $n=1.45$ turns, $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$.

Figure 3.13 shows the axial ratio of the optimum designed curl antenna over the frequency range of 4.0GHz to 5.0GHz. As can be seen, the 3dB axial ratio bandwidth is about 800MHz (from 4.1GHz to 4.9GHz).

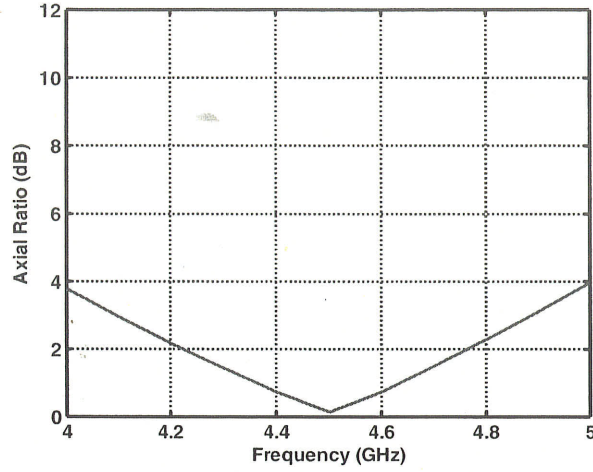
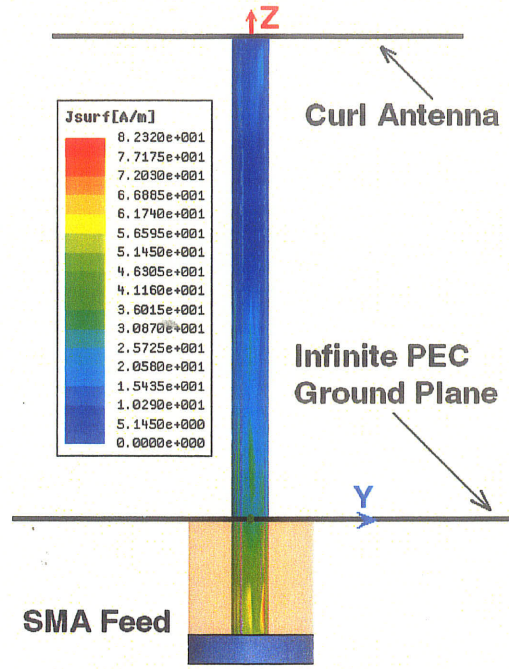
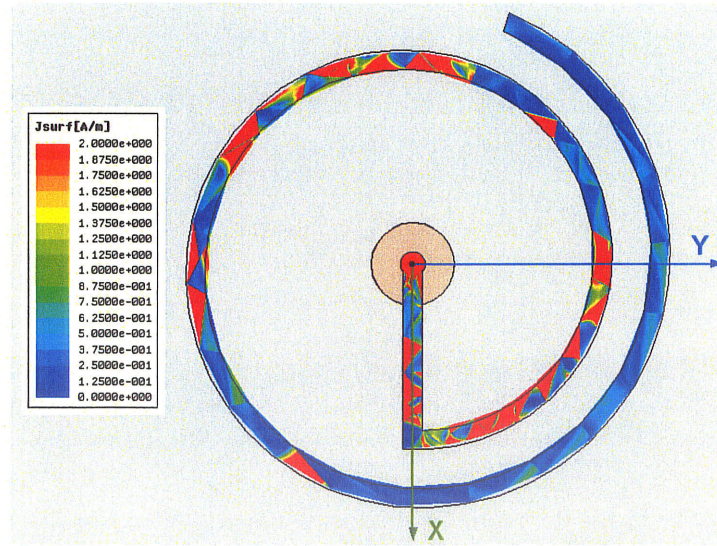


Fig. 3.13: The frequency behavior of the axial ratio for antenna of Fig.3.1, $n=1.45$ turns, $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$.

Finally, the surface current distributions for the three parts of the optimum designed curl antenna over an infinite PEC ground plane are shown in Fig.3.14 at the center frequency of 4.5GHz. As expected, the current magnitude goes to zero as the waves travel toward the end of the curl antenna. The vertical section of the antenna has the higher current density than the other parts since it is directly connected to the SMA feed.



(a)



(b)

Fig. 3.14: The surface current distribution over (a) vertical section (b) radial linear and curved sections of the curl antenna over an infinite PEC ground plane with $n=1.45$ turns, $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$ at $f=4.5\text{GHz}$, with different color scales.

3.5 Summary

In this chapter, a curl antenna over an infinite PEC ground plane was investigated. The operating center frequency was 4.5GHz, from 4-5GHz. Various studies examining the antenna axial ratio in relation to different parameters such as the height, number of turns, and curl constant were carried out using the HFSS v10.1. The results demonstrated that the optimum circular polarization was obtained when the distance between the curl antenna and the PEC ground plane was a quarter-wavelength, which is an expected result. To accomplish the best CP performance, the curl antenna, with the selected parameters, should have $n=1.45$ turns and $a=0.485$ mm/rad. Therefore, a PEC ground plane is not useful in low-profile applications.

Chapter 4

Curl Antenna over Artificial Magnetic Conductor (AMC) Ground Plane

4.1 Introduction

When a planar antenna is backed by a traditional PEC ground plane, the minimum required height is a quarter-wavelength which restricts the use of such ground planes in low profile applications. To overcome the limitations of the required height for traditional ground planes an AMC structure, a newly developed ground plane, may be used. AMC structures consist of periodic metal patches over a grounded dielectric slab. The interesting in-phase reflection phase property of the AMC structures results in the ability to place the planar antennas in close proximity of the AMC ground plane.

In this chapter, a curl antenna over an AMC ground plane is studied to form a low profile antenna. The results will be shown for two finite AMC ground planes: one made of a small array of 4×4 square patches and another one a much smaller array of 2×2 square patches. As previously described, a curl antenna generates circularly polarized waves. The thorough parametric studies will manipulate the number of turns “ n ”, the curl constant “ a ”, and the edge distance “ D_{edge} ”, which is the distance between the outermost patches and the dielectric edge, to investigate how these factors affect the axial ratio. It is shown that the distance between the curl antenna and the AMC surface can be decreased to as small as $0.02\lambda_0$, where λ_0 represents the wavelength in free space, without

sacrificing the axial ratio. All simulations are carried out by the HFSS v10.1 based on the Finite Element method and at the center operating frequency of 4.5GHz ($\lambda_o = 66.67\text{mm}$).

4.2 Study of Unit Cell

As mentioned earlier, an artificial magnetic conductor (AMC) ground plane consists of periodic metallic patches over a grounded dielectric slab. In this study, the unit cell of a square patch is used. Most frequently, the medium between the planar antenna and the AMC ground plane is air, i.e. the curl antenna is suspended in the air. This causes poor mechanical stability, as well as, difficulty in the antenna alignment. To alleviate these problems, a dielectric layer is placed between the antenna and the AMC ground plane. It is important to note that this extra dielectric will change the resonant frequency of the AMC at which the reflection phase is zero. The geometry of the unit cell is shown in Fig. 4.1. The unit cell is designed based on Eqs.2.4 to 2.8 using a correction factor of 0.82, with no upper dielectric layer. Then, they are tuned to operate at the resonant frequency of 4.5GHz using the HFSS v10.1. It is found that the width of the square patch (w) and the periodicity ($w + g$) are equal to 12.8mm and 13.3mm, respectively. The relative permittivity (ϵ_r) of both dielectric materials is 2.5. The height of the lower substrate is equal to 1.5748mm. This selection is based on the available dielectric substrates in the antenna lab.

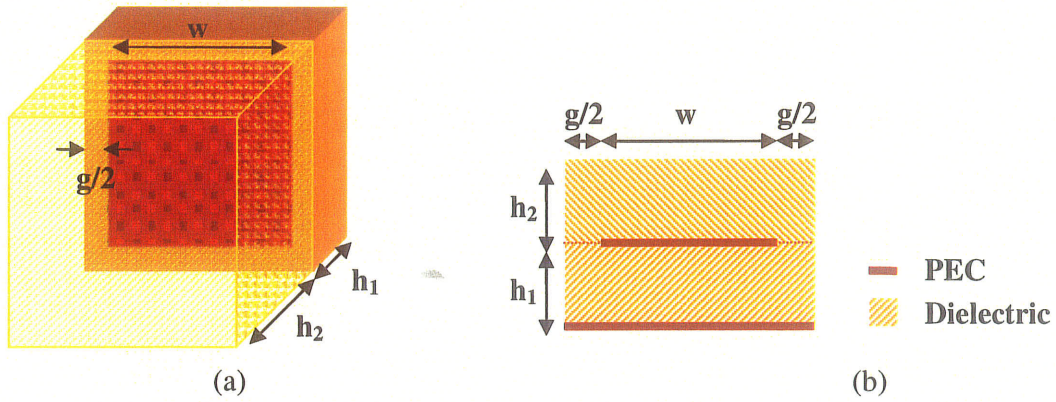


Fig.4.1: (a) 3-D view (b) cross-section view of the unit cell of the AMC ground plane, $w=12.8\text{mm}$, $g=0.5\text{mm}$, $h_1=1.5748\text{mm}$

The reflection phases of the unit cell for two different heights of the upper dielectric layer ($h_2=1.5748\text{mm}$ and 0.7874mm) are shown in Fig. 4.2. The resonance frequency at which the reflection phase goes to zero occurs at $f=4.5\text{GHz}$ when $h_2=1.5748\text{mm}$. As h_2 decreases to 0.7874mm , the resonant frequency increases to 4.62GHz as expected. At the resonant frequency, the structure acts similar to a PMC ground plane. However, the frequency range at which the reflection phase is within ± 90 degrees is conventionally defined as a bandwidth of the AMC ground plane. It should be noted that the HFSS v10.1 calculates the reflection phase by considering an infinite number of unit cells with linked boundary conditions. However, in practice a truncated structure is used.

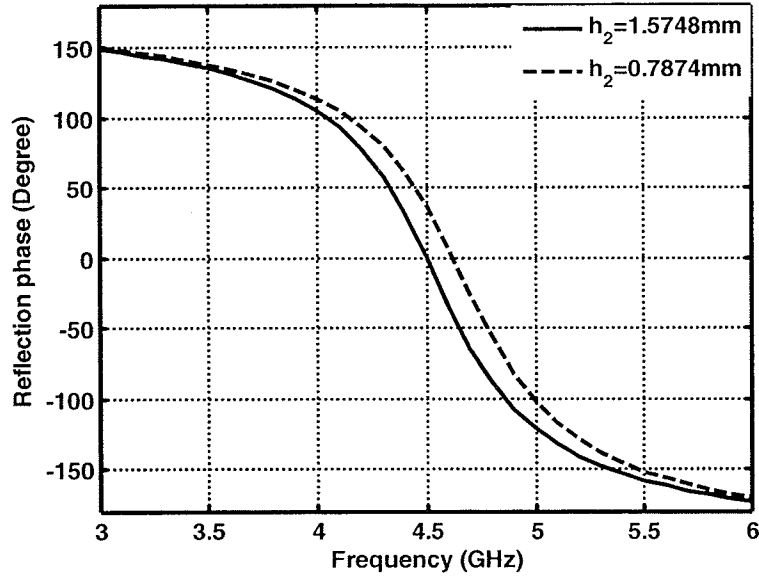


Fig. 4.2: Reflection phase versus frequency of the unit cell shown in Fig. 4.1 for different upper dielectric thicknesses, $\epsilon_r=2.5$, $h_1=1.5748\text{mm}$.

4.3 Curl antenna over AMC ground plane of 4×4 square patches

Sixteen unit cells, in a 4×4 arrangement, are employed to construct an AMC ground plane for the low-profile curl antenna as shown in Fig. 4.3. The curl antenna has $\alpha_{st}=6\pi$. The upper dielectric has a thickness of 1.5748mm, similar to that of the lower dielectric. Based on the available substrates in the antenna lab, Arlon DiClad 527 with a relative dielectric constant of 2.5, is used for both the upper and lower dielectric slabs. The planar curl antenna is etched on the upper dielectric slab, while the squared patches are etched on the lower dielectric slab. Furthermore, the lower dielectric substrate is backed by a flat copper sheet of the same size as the substrate.

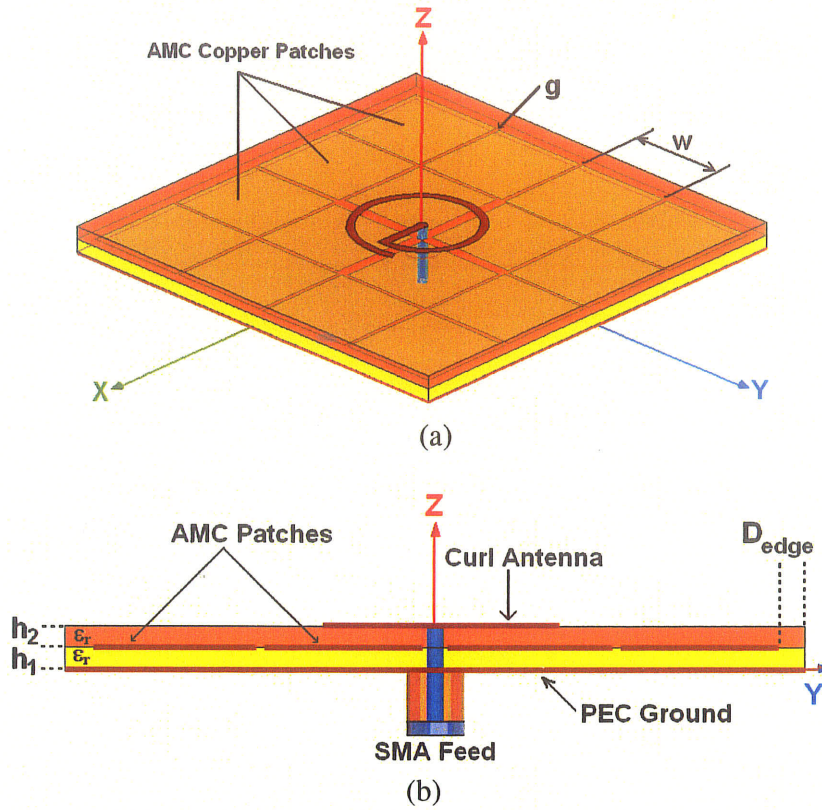


Fig. 4.3: Geometry of the curl antenna over an AMC ground plane consisting of 4×4 conducting copper square patches (a) 3-D view (b) cross-section view

Since the curl antenna is placed on a dielectric material instead of free space, the effective wavelength will be smaller than the wavelength in free space. Consequently, the curl size will also shrink in comparison to the size of a curl antenna over the PEC ground plane described in chapter three.

In this section, the effect of curl number of turns “ n ”, the curl constant “ a ”, and the edge distance “ D_{edge} ” on the axial ratio will be presented. The optimized design parameters are given in Table 4.1, when the distance between the curl antenna and the AMC ground plane is $0.02\lambda_0$. This low-profile antenna is excited by a probe feed located at its center. The impact of the feed position on the antenna axial ratio is also studied.

Table 4.1: The optimum parameters of the single-arm spiral antenna over the AMC ground plane at the center operating frequency of 4.5GHz.

Curl constant “a” (mm/rad)	0.3375
Number of turns “n”	1.07253
α_{st}(radians)	6π
Edge distance “D_{edge}”(mm)	1.55
Height “h₂” (mm)	1.5748=0.02λ_0

4.3.1 Effect of Number of Turn on Axial Ratio (AR)

In this section, the effect of curl number of turns “n” on the axial ratio is studied, while the curl constant “a” and the edge distance “D_{edge}” remain constant at 0.3375mm/rad and 1.55mm, respectively. Figure 4.4 illustrates the axial ratio versus different values of “n”. The best axial ratio, 0.25dB, is obtained when “n” is equal to 1.07253 turns at the center operating frequency of 4.5GHz. As a result, the curl antenna over the dielectric covered AMC ground plane reaches to its active region for a smaller “n” than a curl antenna suspended over a PEC ground plane with an optimum “n” of 1.45. This is due to the fact that the upper dielectric slab will cause a size reduction in the curl antenna as mentioned earlier. The antenna distance from the top of the AMC ground plane is 0.02 λ_0 at the center operating frequency of 4.5GHz, i.e. h₂=1.5748mm.

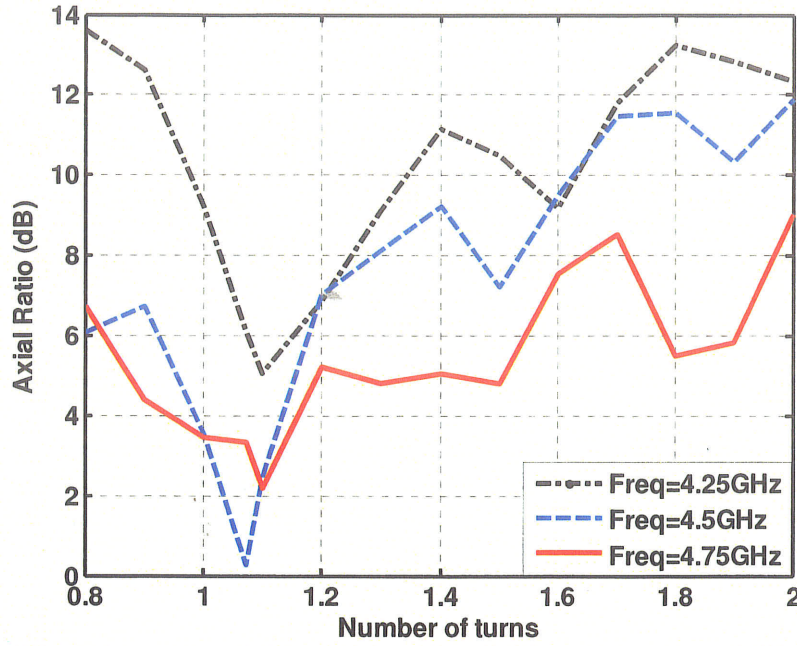


Fig. 4.4: Axial ratio of the antenna shown in Fig.4.3 versus number of turns at $\theta=0^\circ$, when $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$, at $f = 4.25\text{GHz}$, 4.5GHz , and 4.75GHz .

Figure 4.5 shows the axial ratios over the observation angles for different numbers of turns with $n=1.0$, 1.07235 , 1.1 , and 1.2 at different ϕ -planes. As illustrated, the case of $n=1.07235$ has the best performance over the observation angles of $-30^\circ \leq \theta \leq +30^\circ$ at all planes. Whereas the minimum axial ratios for the cases of $n=1$ and 1.1 turns are well above 0.25dB and their local minima occur over different observation angles at each ϕ -plane. Finally, the minimum axial ratio for the case of $n=1.2$ is near 2dB at the $\theta=-70^\circ$ and $\phi=90^\circ$ with a relatively high axial ratio at the other ϕ -planes.

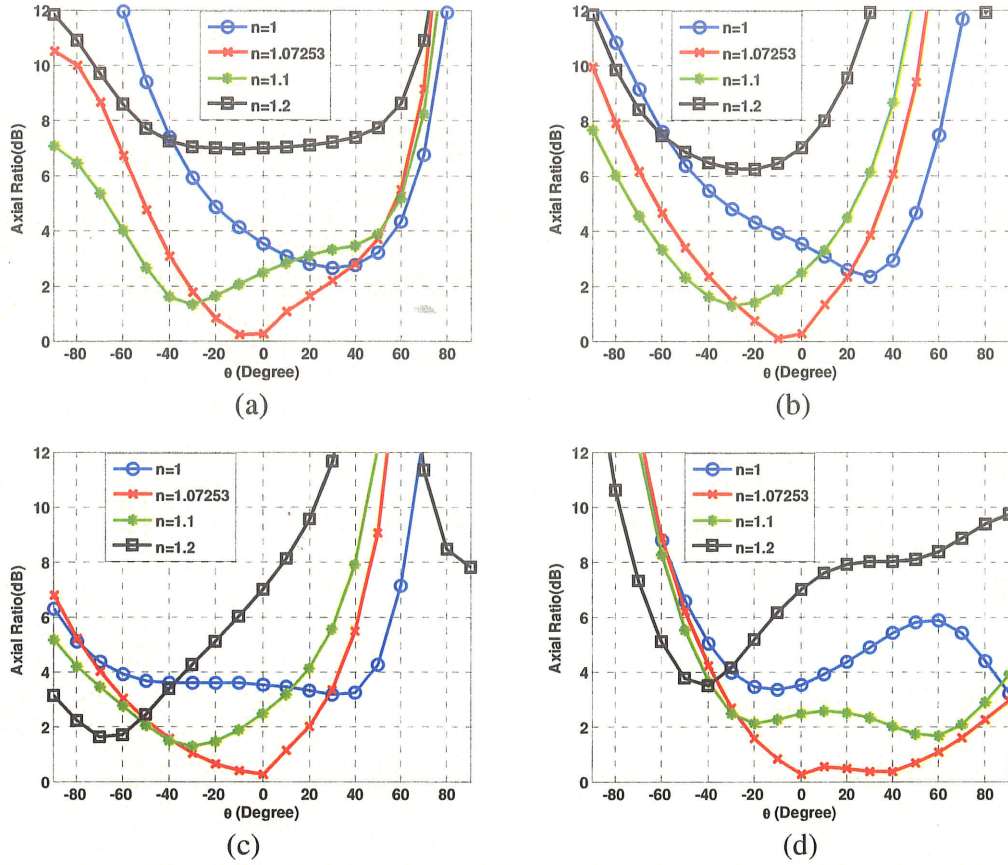


Fig. 4.5: Axial ratios of the antenna shown in Fig.4.3 for different number of turns ($n=1, 1.07253, 1.1, 1.2$) when $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$, and $f=4.5\text{GHz}$, at (a) $\phi=0^\circ$ (b) $\phi=45^\circ$ (c) $\phi=90^\circ$ (d) $\phi=135^\circ$ planes, $h_1=h_2=1.5748\text{mm}$, $\epsilon_r=2.5$.

4.3.2 Effect of Curl Constant on Axial Ratio (AR)

In this section, the impact of curl constant “a” on the axial ratio of the antenna shown in Fig.4.3 is investigated, while the number of turn “n” and the edge distance “ D_{edge} ” are kept unchanged and they are equal to 1.07253 turns and 1.55mm, respectively. Figure 4.6 depicts the axial ratio versus different curl constants. The best axial ratio, 0.25dB, is obtained at the center operating frequency of 4.5GHz when “a” is equal to 0.3375mm/rad, whereas the optimum “a” of the curl antenna over a PEC ground plane was found to be 0.485mm/rad as studied in chapter three. Thus, it is observed that

the curl size shrinks when it is placed over an AMC ground plane rather than suspended over a PEC ground plane. This is because of the effect of the upper dielectric slab, which makes the effective wavelength smaller. The distance between the antenna and the top of the AMC ground plane is $0.02\lambda_0$ at the center operating frequency of 4.5GHz.

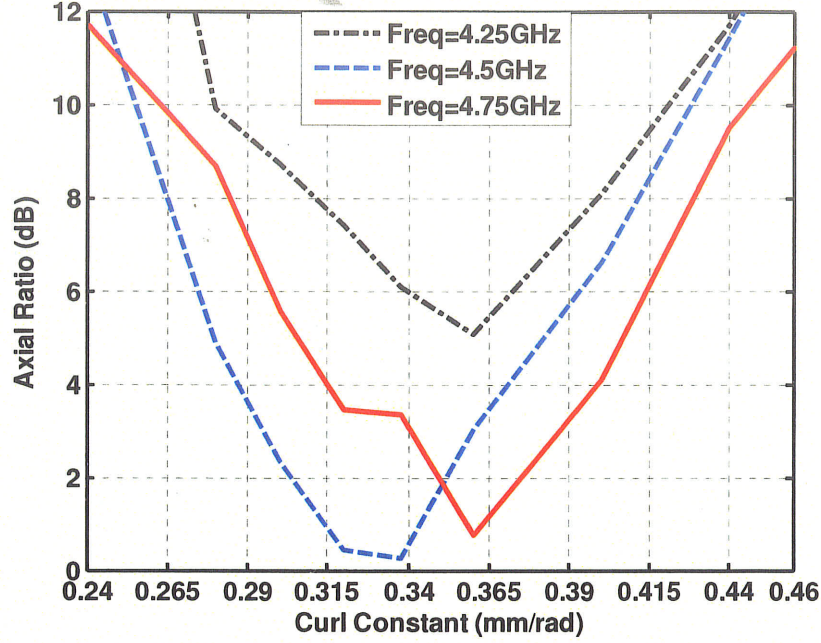


Fig. 4.6: Axial ratio of the antenna shown in Fig.4.3 versus curl constant at $\theta=0^\circ$, when $n=1.07253$, $D_{\text{edge}}=1.55\text{mm}$, at $f = 4.25\text{GHz}$, 4.5GHz , and 4.75GHz .

Figure 4.7 shows the axial ratio over the observation angles for different curl constants, $a=0.280$, 0.300 , 0.3375 , and 0.360mm/rad at different ϕ -planes. As can be observed, the case of $a=0.3375\text{mm/rad}$ has the best performance approximately over the observation angles of $-30^\circ \leq \theta \leq +30^\circ$ at all planes. In contrast, the other cases have different minimum axial ratios at each ϕ -plane, resulting in a poor CP performance. For instance, the case of $a=0.280\text{mm/rad}$ has a minimum axial ratio of 5dB around boresight angle, $\theta=0^\circ$, at $\phi=0^\circ$ plane with a different local minima at other ϕ -planes.

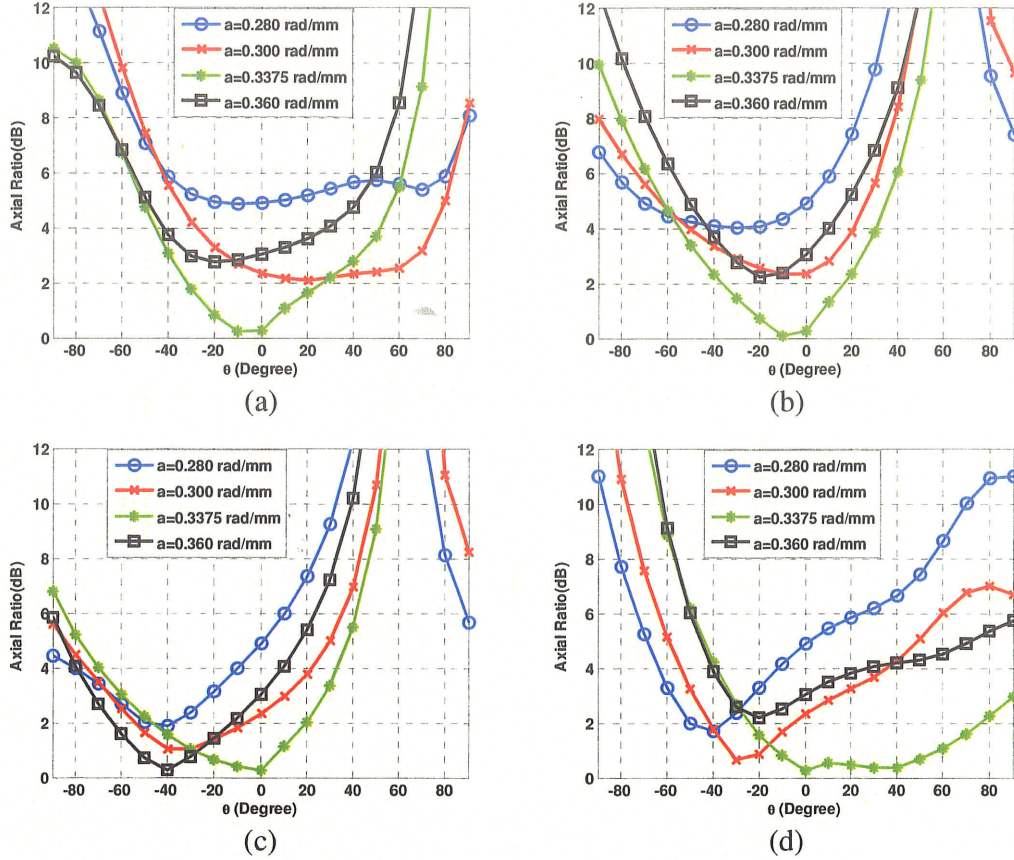


Fig. 4.7: Axial ratios of the antenna shown in Fig.4.3 for different curl constants (0.280 mm/rad, 0.300 mm/rad, 0.3375 mm/rad, 0.360 mm/rad) when $n=1.07325$, $D_{\text{edge}}=1.55\text{mm}$, and $f=4.5\text{GHz}$, at (a) $\phi=0^\circ$ (b) $\phi=45^\circ$ (c) $\phi=90^\circ$ (d) $\phi=135^\circ$ planes, $h_1=h_2=1.5748\text{mm}$, $\epsilon_r=2.5$.

4.3.3 Effect of Edge Distance on Axial Ratio (AR)

The truncated periodic structures have normally an edge distance of $g/2$, assuming “g” is the gap between the two adjacent patches. As mentioned earlier, “g” is 0.5mm in this study, which is very small in comparison to the wavelength at the center operating frequency of 4.5GHz. As a result, the strong fringing field exists on the AMC edges. To obtain the best possible axial ratio, one can optimize the edge distance. This parameter, D_{edge} , is shown in Fig.4.8.

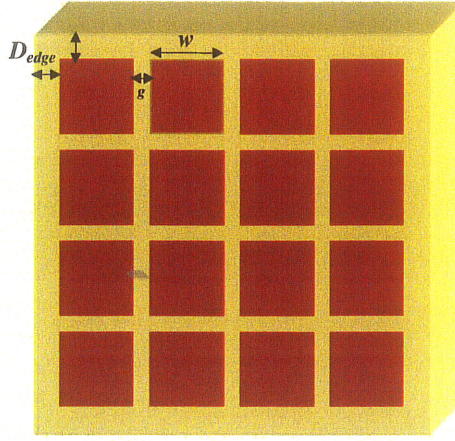


Fig. 4.8: Geometry of AMC ground plane with illustration of D_{edge}

In this section, the effect of the edge distance “ D_{edge} ” on the axial ratio of the antenna shown in Fig.4.3 is investigated. The curl constant “ a ” and the number of turns “ n ” are constant and they are equal to 0.3375mm/rad and 1.07253 turns, respectively. Figure 4.9 shows the axial ratio versus different edge distances. The best axial ratio of 0.25dB is obtained when “ D_{edge} ” is equal to 1.55mm at the center operating frequency of 4.5GHz. This improvement is compared with the normal truncated periodic structure with $D_{\text{edge}}=g/2=0.25\text{mm}$, which has a higher axial ratio of 1.5dB. Interestingly, the optimized D_{edge} is very small in comparison to the planar size of the AMC ground plane, allowing the entire antenna to be considered a low-profile and small structure. There is a fluctuation in the axial ratio up to D_{edge} of 5.5mm, while the axial ratio grows thereafter. The distance between the antenna and the top of the AMC ground plane, h_2 , is $0.02\lambda_0$ at the center operating frequency of 4.5GHz.

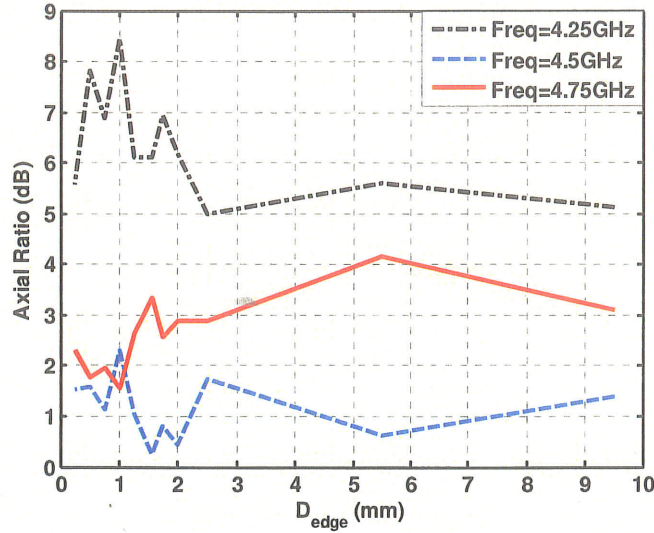


Fig. 4.9: Axial ratio of the antenna shown in Fig.4.3 versus edge distance at $\theta=0^\circ$, when $a=0.3375\text{mm/rad}$, $n=1.07253$, at $f = 4.25\text{GHz}$, 4.5GHz , and 4.75GHz .

Also, the axial ratio of the two cases of $D_{\text{edge}}=g/2=0.25\text{mm}$ and $D_{\text{edge}}=1.55\text{mm}$ are compared and shown in Fig. 4.10 at different ϕ -planes. When D_{edge} is equal to 0.25mm , local minima occurs at different observation angles for each ϕ -plane. For instance, these minima are obtained at $\theta=-20^\circ$ and $\theta=+40^\circ$ at $\phi=0^\circ$ and $\phi=135^\circ$ planes, respectively. While for the case of the $D_{\text{edge}}=1.55\text{mm}$ all local minima occur closely at the boresight angle with the 3dB axial ratio beamwidth over $-30^\circ \leq \theta \leq +30^\circ$. This beamwidth is referred to the observation angles within which the axial ratio is equal or less than 3dB .

From these parametric studies of the curl antenna over an AMC ground plane of 4×4 square patches, the best axial ratio is found when $a=0.3375\text{mm/rad}$, $n=1.07253$ turns, and $D_{\text{edge}}=1.55\text{mm}$, as given in Table 4.1. The planar size of the new ground plane is $0.837\lambda_0 \times 0.837\lambda_0$ and the distance between the curl antenna and the top of the AMC surface is $0.02\lambda_0$ at the center operating frequency of 4.5GHz , where λ_0 is the free space wavelength.

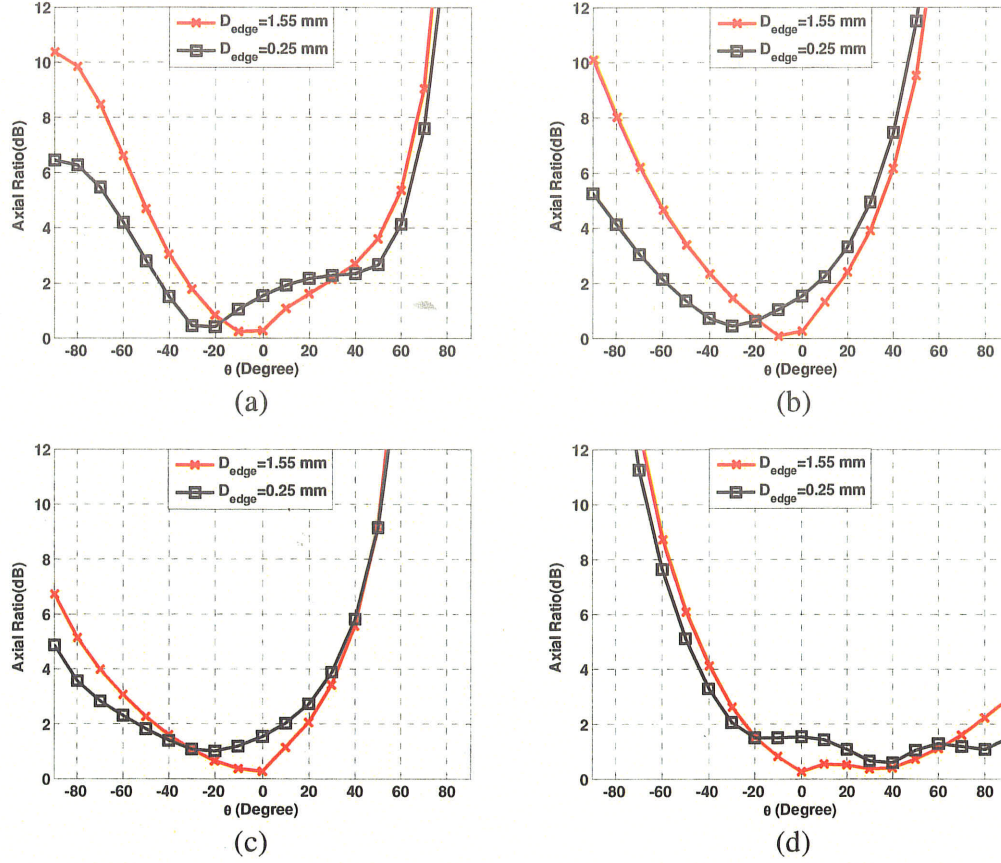


Fig. 4.10: Axial ratios of the antenna shown in Fig.4.3 for different edge distance ($D_{\text{edge}} = 0.25\text{mm}$, 1.55mm) when $a=0.3375\text{mm/rad}$, $n=1.07253$, and $f=4.5\text{GHz}$, at (a) $\phi=0^\circ$ (b) $\phi=45^\circ$ (c) $\phi=90^\circ$ (d) $\phi=135^\circ$ planes.

Figure 4.11 shows the axial ratio at different ϕ -planes for the optimum values, given in Table 4.1, at the center operating frequency of 4.5GHz. As can be seen, the 3dB axial ratio beamwidth occurs over the observation angles of $-30^\circ \leq \theta \leq +30^\circ$. Moreover, the 3dB axial ratio beamwidth is broader at $\phi=135^\circ$ comparing to others. To show the frequency behavior of the above optimum case, Fig. 4.12 depicts the axial ratios at two different frequencies of 4.25GHz and 4.75GHz. The axial ratio is increased to about 6dB and 3dB at the frequency of 4.25GHz and 4.75GHz, respectively, at the boresight direction. This abrupt change in the axial ratio is due to the resonant structure of the AMC ground plane.

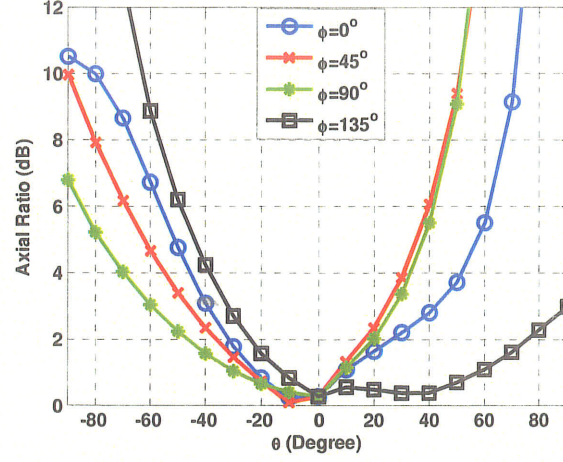


Fig. 4.11: Axial ratio of the antenna shown in Fig. 4.3 for the optimum case ($n=1.07253$ turns, $a=0.3375\text{mm/rad}$, and $D_{\text{edge}}=1.55\text{mm}$) at different ϕ -planes and $f=4.5\text{GHz}$.

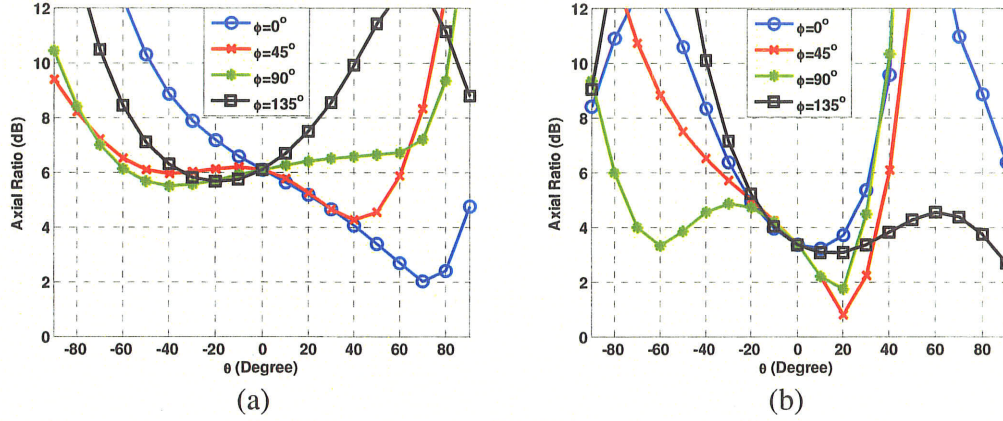


Fig. 4.12: Axial ratios of the antenna shown in Fig. 4.3 for the optimum case ($n=1.07253$ turns, $a=0.3375\text{mm/rad}$, and $D_{\text{edge}}=1.55\text{mm}$) at different ϕ -planes (a) $f = 4.25\text{GHz}$ (b) $f = 4.75\text{GHz}$.

The RHCP and LHCP gains are plotted in Fig.4.13 at principal planes for this optimum design at the center operating frequency of 4.5GHz. As expected, the antenna produces RHCP waves with the gain of 8dBic at the boresight angle. The LHCP, cross polar, component is 30dB below the RHCP, coplar, component at the boresight angle. Also, Fig. 4.14 illustrates the right-hand and left-hand circular gain patterns at two

different frequencies of 4.25GHz and 4.75GHz. The peak value of the RHCP gain is almost unchanged. However, the cross polarization performance degrades. That is, the cross polar components are 10dB and 15dB below the copolar one at the frequency of 4.25GHz and 4.75GHz, respectively.

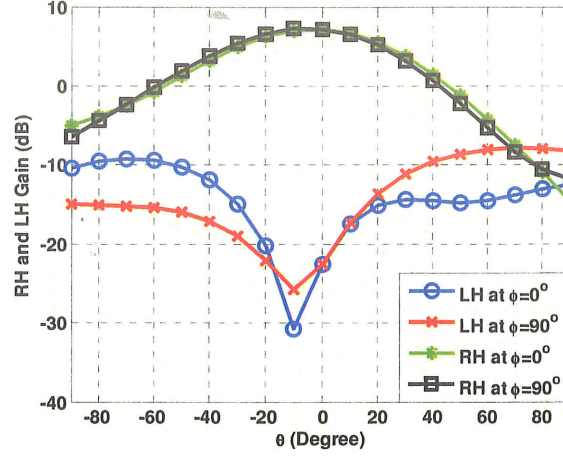


Fig. 4.13: Right-Hand and Left-Hand, copolar and cross polar, gains of the antenna shown in Fig. 4.3 for the optimum case ($n=1.07253$ turns, $a=0.3375\text{mm/rad}$, and $D_{\text{edge}}=1.55\text{mm}$) at $\phi=0^\circ$ and 90° planes and $f=4.5\text{GHz}$.

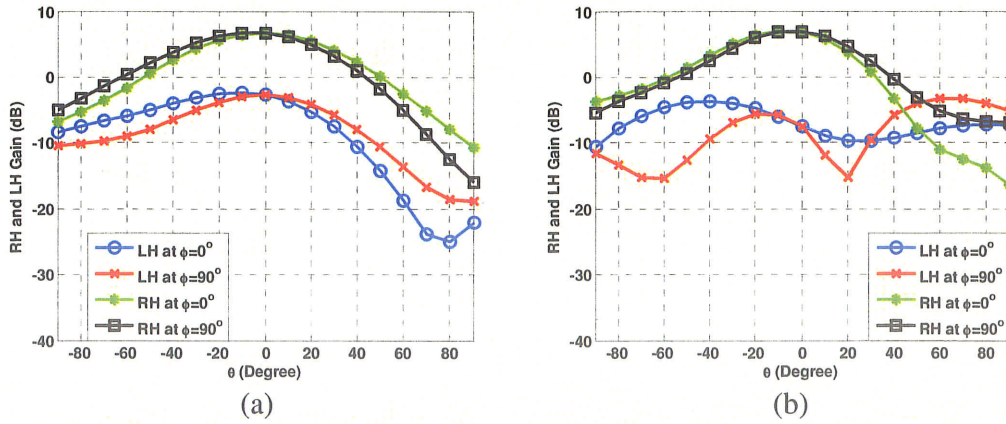


Fig. 4.14: Right-Hand and Left-Hand, copolar and cross polar, gains of the antenna shown in Fig. 4.3 for the optimum case ($n=1.07253$ turns, $a=0.3375\text{mm/rad}$, and $D_{\text{edge}}=1.55\text{mm}$) at $\phi=0^\circ$ and 90° planes and (a) $f=4.25\text{GHz}$ (b) $f=4.75\text{GHz}$.

The peak value of the RHCP gain of the single-arm curl antenna over both infinite PEC and finite AMC ground planes are compared in Fig. 4.15. Both cases have almost flat RHCP gains over the frequency range of 4.3-4.8GHz. The gain variation is less than 1dB for the PEC case over the frequency range of 4-5GHz, whereas the RHCP gain drops sharply at the upper and lower frequencies for the AMC case because of its resonance behavior.

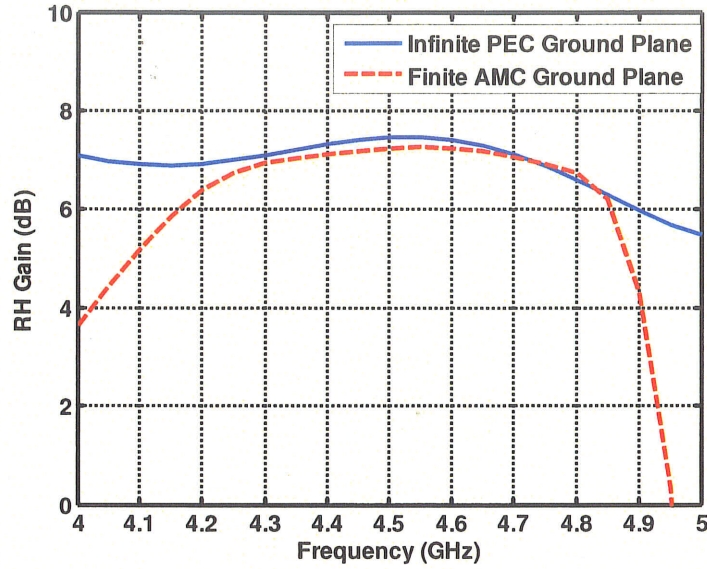


Fig. 4.15: Right-Hand gains of the single-arm spiral curl antenna over an infinite PEC shown in Fig.3.1 when $\alpha_{st} = 6\pi$, $n=1.45$, $a = 0.485\text{mm/rad}$, $h = 16.67\text{mm} = \lambda_o/4$, and the AMC ground plane shown in Fig. 4.3, when $\alpha_{st}=6\pi$, $n=1.07253$, $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$ at $\theta=0^\circ$.

The normalized RHCP and LHCP radiation patterns for the optimum design are also illustrated in Fig. 4.16 at $\phi=0^\circ$, 45° , 90° , and 135° planes. This figure shows the LHCP, cross polar, component is at least 15dB below the maximum RHCP one and it is

negligible over positive observation angles in the $\phi=135^\circ$ plane. The most symmetric pattern is observed in the $\phi=0^\circ$ plane.

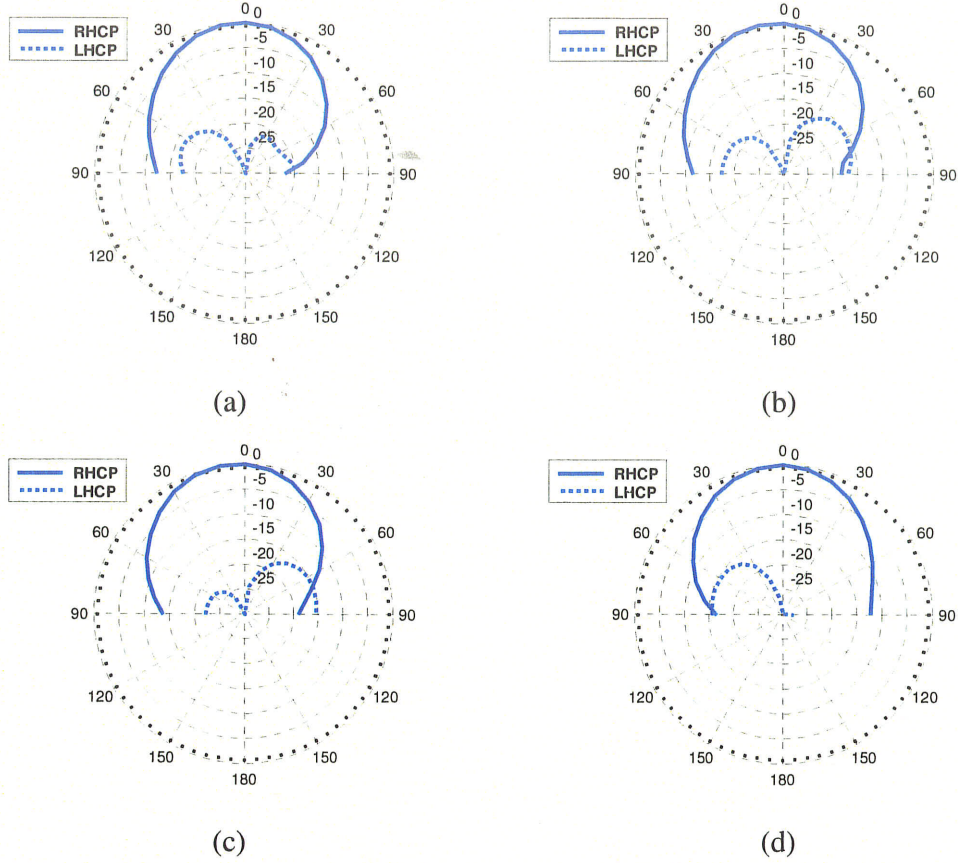
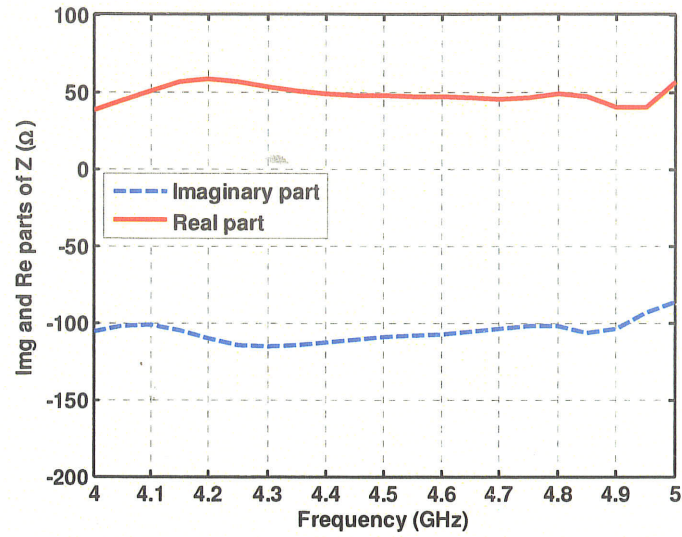


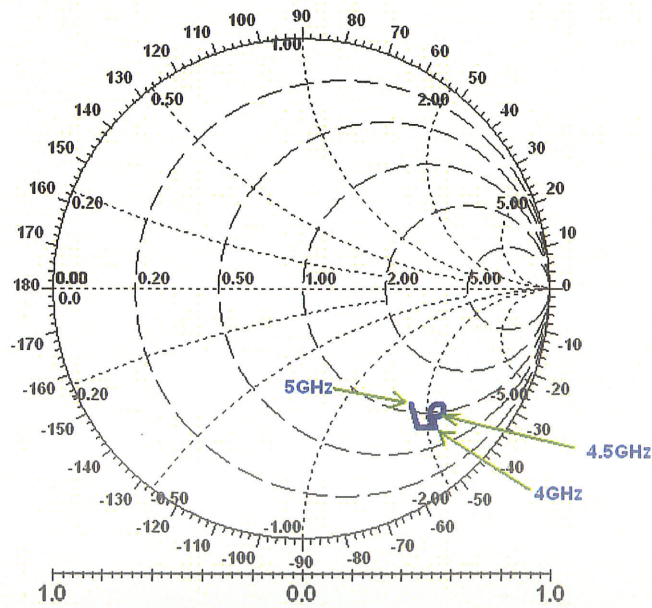
Fig. 4.16: Normalized radiation pattern of the antenna shown in Fig.4.3 with optimum parameters $n=1.07253$, $a=0.3375$ mm/rad, and $D_{\text{edge}}=1.55$ mm for different ϕ planes: (a) $\phi=0^\circ$ (b) $\phi=45^\circ$ (c) $\phi=90^\circ$ (d) $\phi=135^\circ$ at $f=4.5$ GHz.

Furthermore, the optimized curl antenna over the AMC ground plane is excited by a probe feed located at its center. The real and imaginary parts of the input impedance are shown in Fig. 4.17a. As can be seen, the real part is almost near 50Ω with a constant capacitive effect, i.e. negative imaginary part, over the frequency range of 4.0-5.0GHz. Therefore, the antenna can be matched to a 50Ω -system using standard matching techniques. Also, the Smith chart of the input impedance is given in Fig. 4.17b. This also

confirms that the input impedance is almost constant over the operating frequency bandwidth.



(a)



(b)

Fig. 4.17: (a) Real and Imaginary parts (b) Smith chart of the input impedance of the antenna shown in Fig.4.3 for the optimum case ($n=1.07253$ turns, $a=0.3375\text{mm/rad}$, and $D_{\text{edge}}=1.55\text{mm}$).

The frequency behavior of the axial ratio of the optimized curl antenna over an AMC ground plane is shown in Fig. 4.18 at the boresight angle, $\theta=0^\circ$. The 3dB axial ratio bandwidth is 360MHz from 4.36GHz to 4.72GHz. The minimum axial ratio is obtained at the resonant frequency of the AMC structure at $f=4.5\text{GHz}$ as expected.

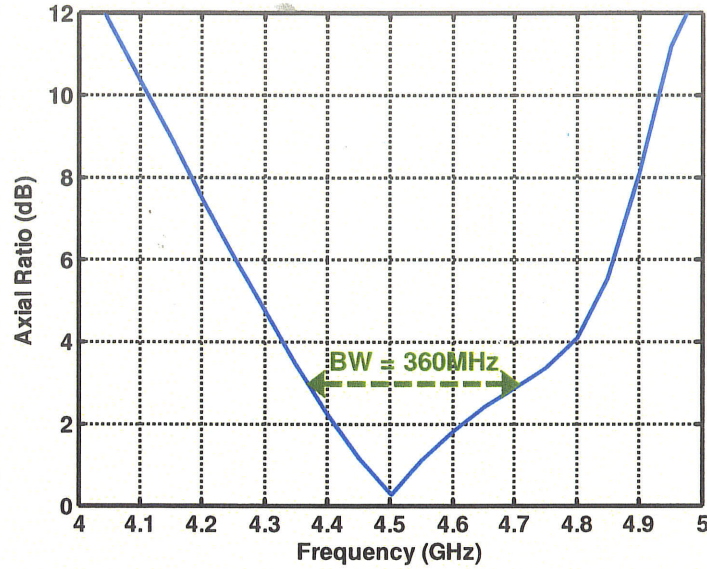


Fig. 4.18: Axial ratio of the antenna shown in Fig. 4.3 versus frequency for the optimum case ($n=1.07253$ turns, $a=0.3375\text{mm/rad}$, and $D_{\text{edge}}=1.55\text{mm}$) at $\theta=0^\circ$.

Finally, the surface current distributions for the three parts of the optimum designed curl antenna over the AMC ground plane are shown in Fig.4.19 at the center frequency of 4.5GHz. As expected, the current magnitude goes to zero as the waves travel toward the end of the curl antenna. The current is uniformly distributed over the vertical section for this low-profile antenna.

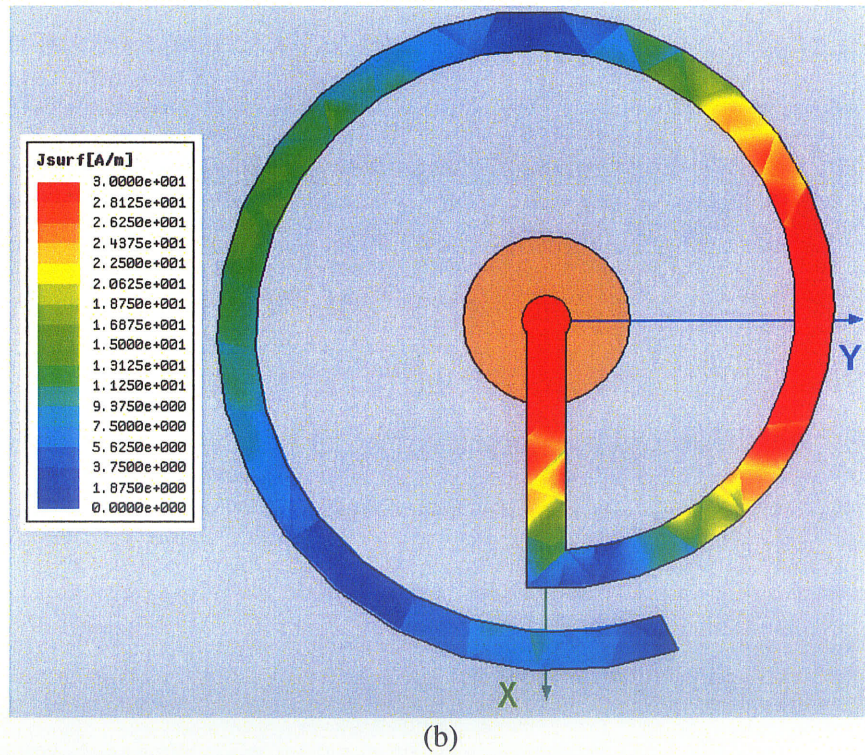
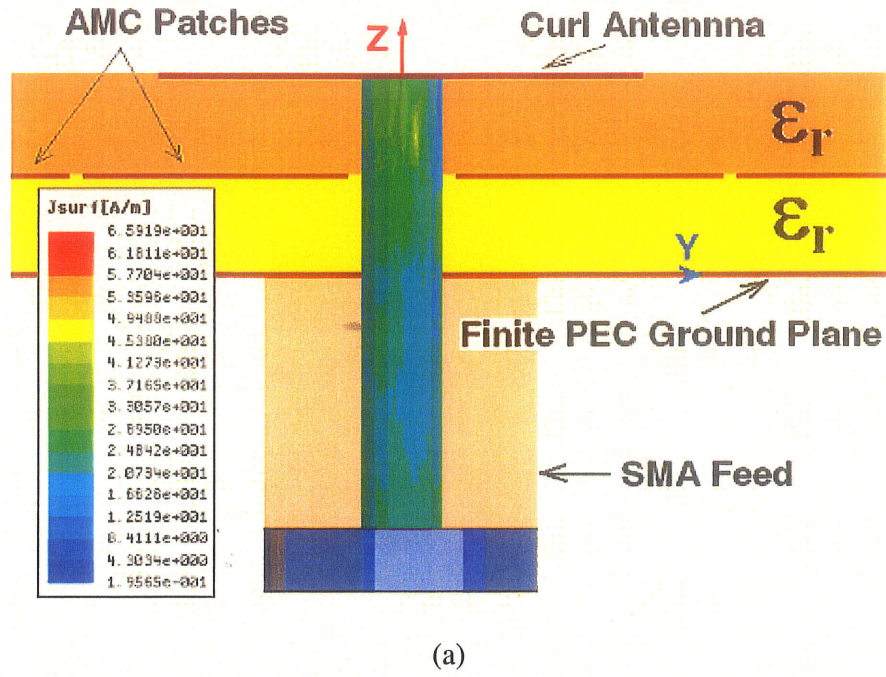


Fig. 4.19: The surface current distribution over (a) vertical section (b) radial linear and curved sections of the low-profile curl antenna over the AMC ground plane with $n=1.07253$ turns, $a=0.3375\text{mm/rad}$, $\epsilon_r=2.5$, and $D_{edge}=1.55\text{mm}$ at $f=4.5\text{GHz}$, with different color scales.

4.3.4 Offset feeding

The curl antenna under study has three parts: the vertical feed probe, the radial linear and spiral parts. When a curl antenna is placed over a traditional PEC ground plane, the radial linear section is normally used to feed the curl at its center. This straight part of the antenna has no significant effect on its CP performance as reported in [40].

In this section, the effect of this radial linear part of the curl antenna is investigated when it is placed over the AMC ground plane. The straight part is removed and the probe feed is located at the starting point of the spiral part at $x=a$ $\alpha_{st}=6.36\text{mm}$ and $y=0$. The AMC ground plane is the same 4×4 square patch array with no vertical vias, similar to that in former studies. The unit cell specification is the same as that described in section 4.2. That is, $w=12.8\text{mm}$, $g=0.5\text{mm}$, $h_1=h_2=1.5748\text{mm}$, and $\epsilon_r=2.5$. The geometry of the offset fed curl antenna is shown in Fig. 4.20. The designed parameters are selected from the optimized ones found in section 4.3.3. That is, $\alpha_{st}=6\pi$, $a=0.3375\text{mm/rad}$, $n=1.07253$ turns, $D_{edge}=1.55\text{mm}$. The axial ratio versus frequency of the above antenna is shown in Fig. 4.21 at the boresight angle, $\theta=0^\circ$.

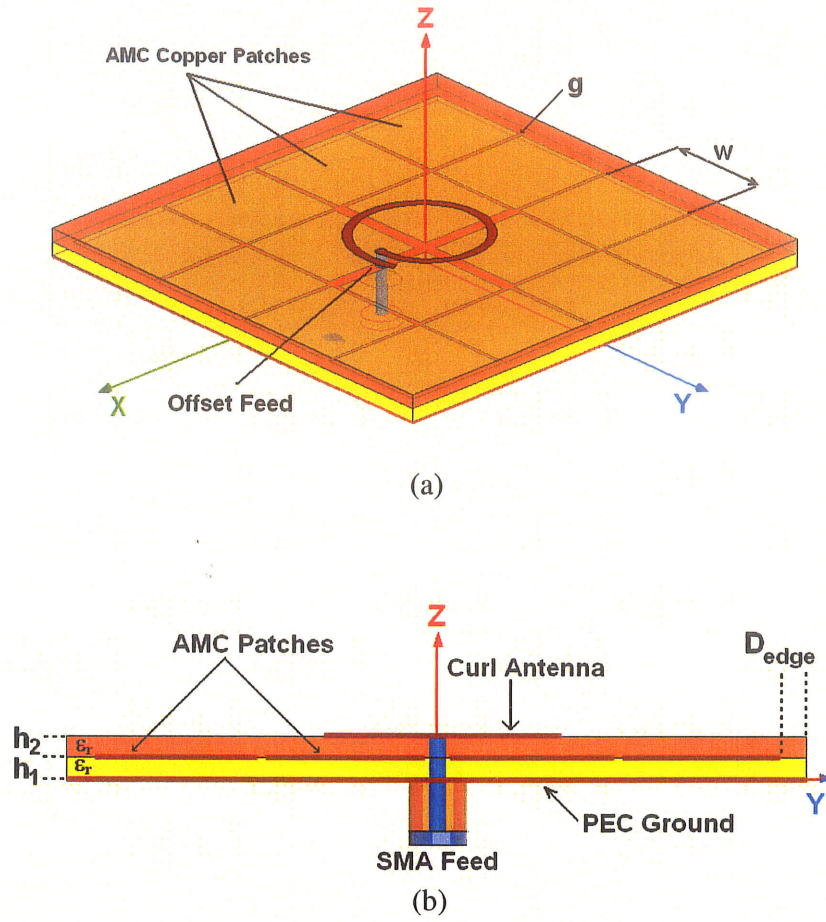


Fig. 4.20: (a) top view (b) cross-section view of the offset fed curl antenna over AMC ground plane, $\alpha_{st}=6\pi$, $a=0.3375\text{mm/rad}$, $n=1.07253$ turns, $D_{edge}=1.55\text{mm}$, with feed located at $x=6.36\text{mm}$ and $y=0$.

In Fig. 4.21, the axial ratio at the center operating frequency of 4.5GHz is increased to 2dB. The minimum axial ratio occurs at the frequency of 4.8GHz. Unlike the PEC ground plane, the radial part of the curl antenna changes the CP performance of the antenna over the AMC ground plane. This is caused by the close proximity of the antenna to the AMC ground plane, which behaves as a resonant structure.

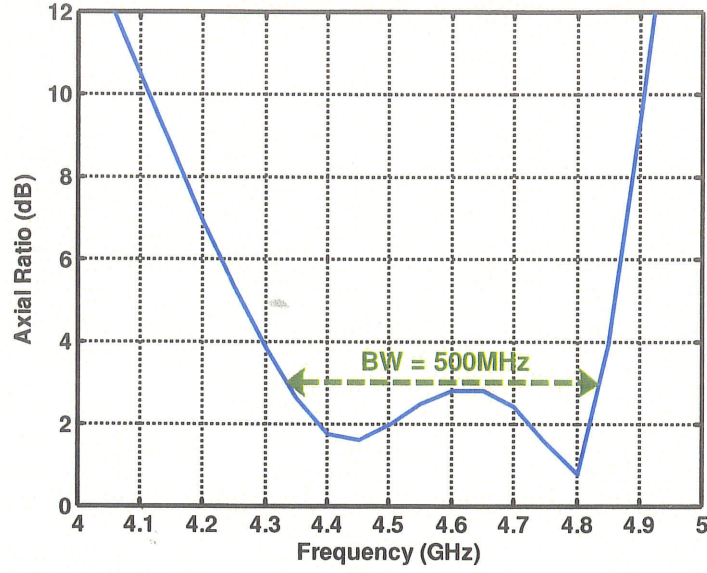


Fig. 4.21: Axial ratio of the antenna shown in Fig. 4.20 versus frequency, when $n=1.07253$ turns, $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$ at $\theta=0^\circ$.

Figure 4.22 shows the axial ratio at different ϕ -planes for the two frequencies of 4.5GHz and 4.8GHz. The 3dB axial ratio beamwidth is narrower at the frequency of 4.8GHz. However, it provides better CP performance near the boresight direction.

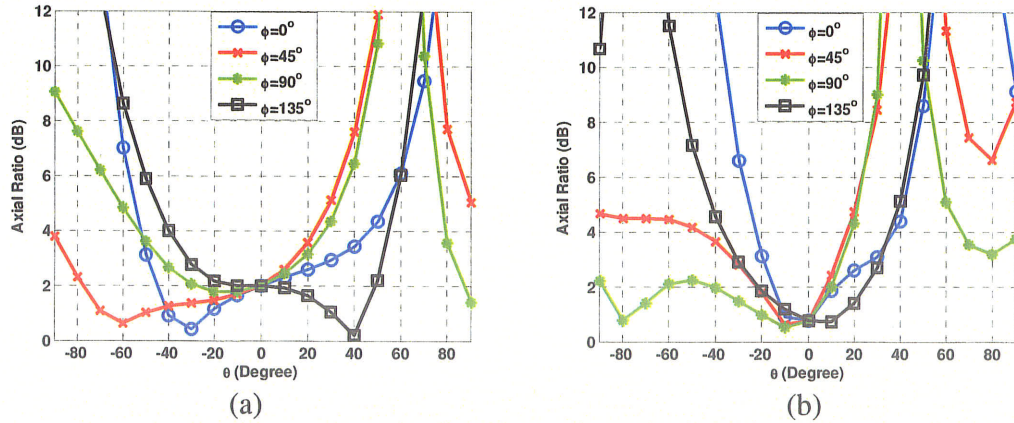


Fig. 4.22: Axial ratio of the antenna shown in Fig.4.20, when $n=1.07253$ turns, $D_{\text{edge}}=1.55\text{mm}$, $a=0.3375\text{mm/rad}$ at different ϕ -planes (a) $f=4.5\text{GHz}$ (b) $f=4.8\text{GHz}$.

Further attempts were made to tune the offset fed curl antenna to the center operating frequency of 4.5GHz. It is shown that, this can be done if the curl part is just extended toward its center without changing the feed position as shown in Fig. 4.23. The extra needed turn is found to be a half turn. That is, the feed location is still located at $x=6.36\text{mm}$ and $y=0$. The curl constant and D_{edge} are 0.3375mm/rad and 1.55mm , respectively, as above. Geometrically, the start angle of the curl part is decreased to 5π . Thus, the number of turns is increased to 1.57253. Table 4.2 summarizes the optimized parameters.

Table 4.2: The optimum parameters of the single-arm offset fed spiral antenna over the AMC ground plane at the center operating frequency of 4.5GHz.

Curl constant “a” (mm/rad)	0.3375
Number of turns “n”	1.57253
α_{st}(radians)	5π
Edge distance “D_{edge}”(mm)	1.55
Height “h_2” (mm)	$1.5748=0.02\lambda_0$

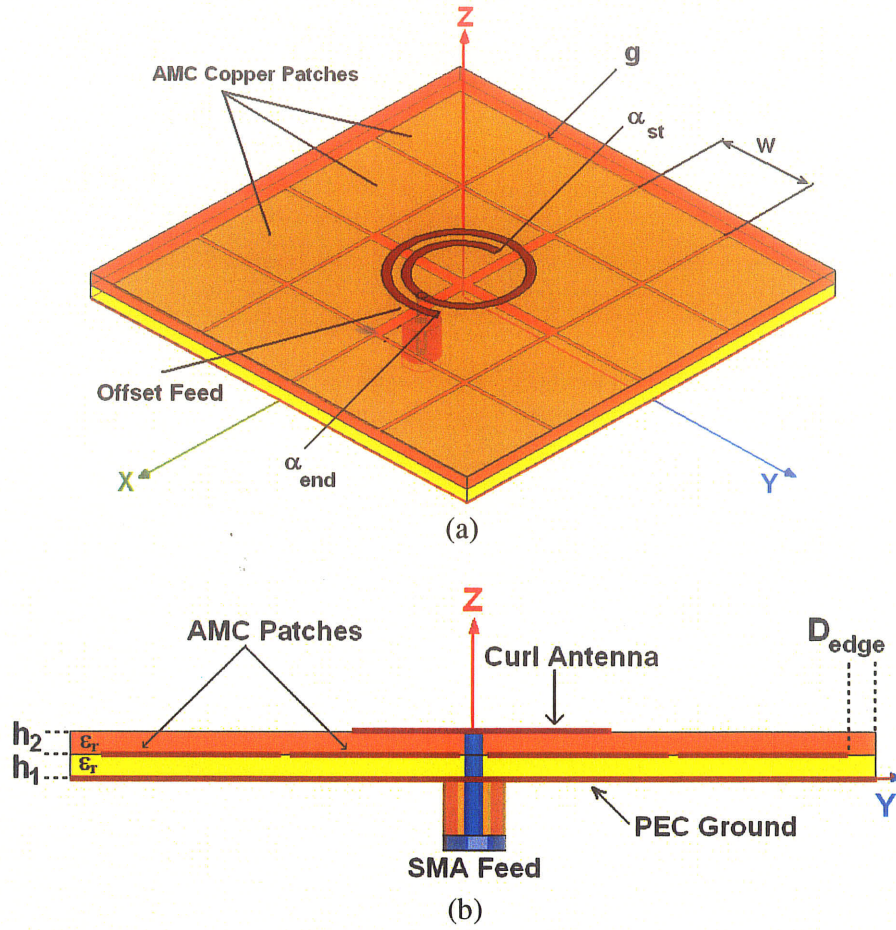


Fig. 4.23: (a) top view (b) cross-section view of the offset fed curl antenna over the AMC ground plane, $\alpha_{st}=5\pi$, $a=0.3375\text{mm/rad}$, $n=1.57253$ turns, $D_{edge}=1.55\text{mm}$, with feed located at $x=6.36\text{mm}$ and $y=0$, $h_1=h_2=1.5748\text{mm}$, $\epsilon_r=2.5$.

The resulting axial ratio versus frequency is illustrated in Fig. 4.24 at the boresight angle, $\theta=0^\circ$. Now, the desired frequency of 4.5GHz has the minimum axial ratio of 0.2dB.

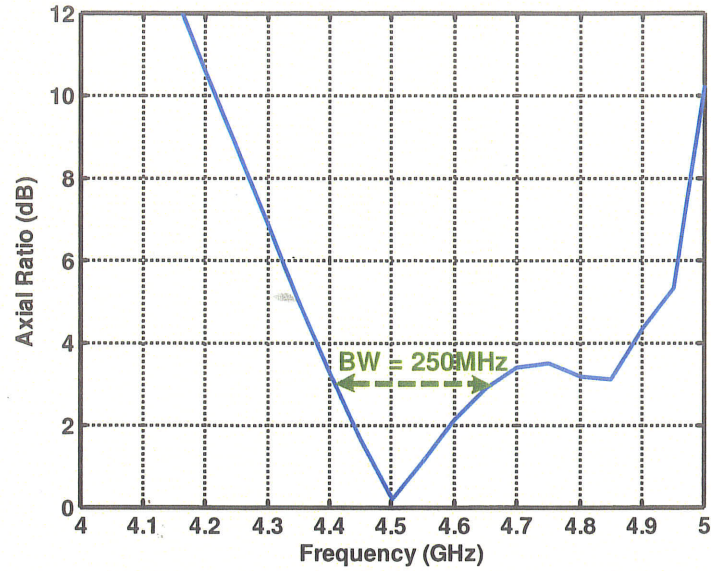


Fig. 4.24: Axial ratio of the antenna shown in Fig. 4.23 versus frequency, when $n=1.57253$ turns, $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$ at $\theta=0^\circ$.

Figure 4.25 depicts the axial ratio of the antenna shown in Fig. 4.23 at $\phi=0^\circ$, 45° , 90° , and 135° planes. The 3dB axial ratio beamwidth occurs over the observation angles of $-30^\circ \leq \theta \leq +25^\circ$ at all planes. This beamwidth is just 5 degrees less than that of the center-fed curl antenna given in section 4.3.3.

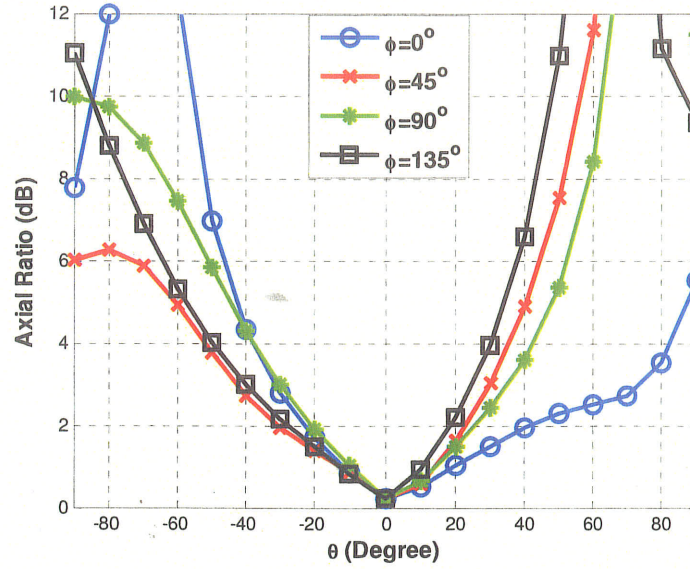


Fig. 4.25: Axial ratio of the antenna shown in Fig. 4.23, when $n=1.57253$ turns, $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$, and $f=4.5\text{GHz}$ at $\phi=0^\circ$, 45° , 90° , and 135° planes, $h_1=h_2=1.5748\text{mm}$, $\epsilon_r=2.5$.

The surface current distributions for the vertical and curved parts of the offset-fed curl antenna, shown in Fig.4.23, over the AMC ground plane are shown in Fig.4.26 at the center frequency of 4.5GHz. The current magnitude nearly goes to zero as the waves travel toward the end of the curl antenna.

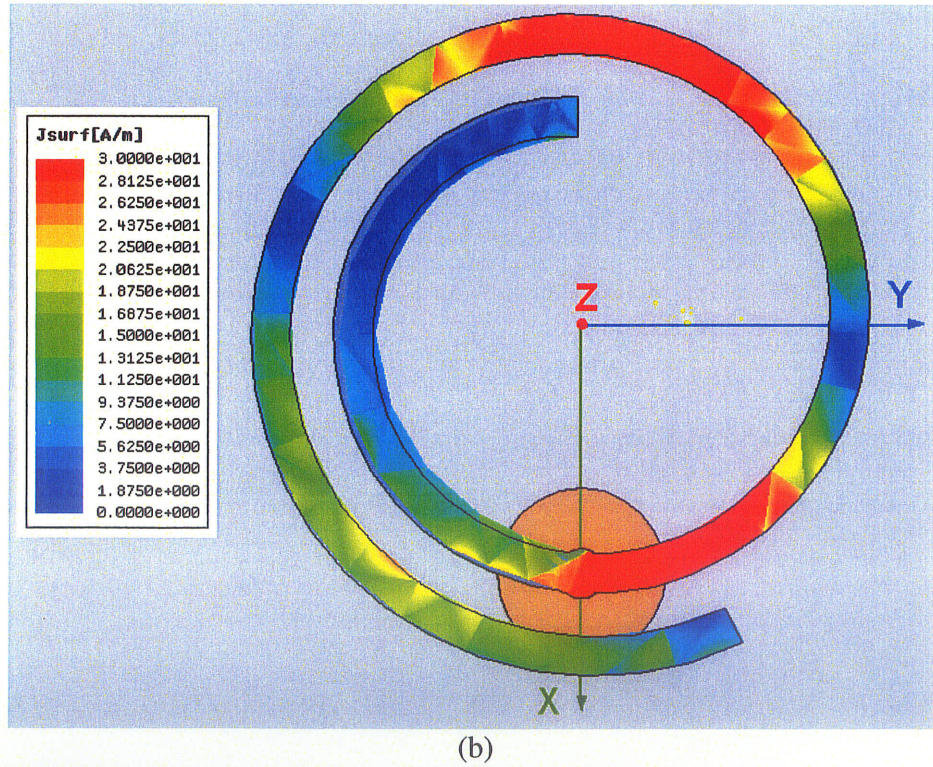
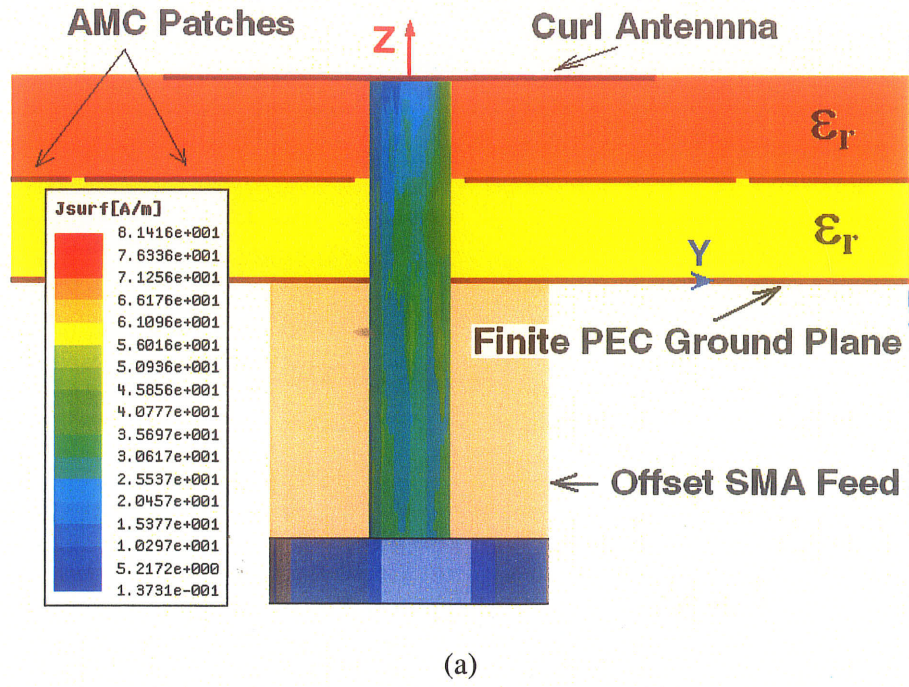


Fig. 4.26: The surface current distribution over (a) vertical section (b) curved section of the offset-fed curl antenna over the AMC ground plane with $n=1.57253$ turns, $\epsilon_r=2.5$, $a=0.3375\text{mm/rad}$, and $D_{\text{edge}}=1.55\text{mm}$ at $f=4.5\text{GHz}$, with different color scales.

4.4 Curl Antenna over AMC Ground Plane of 2x2 Square Patches

In this section, the center-fed curl antenna is investigated over the AMC ground plane consisting of a 2x2 array of square patches. The main motivation is to decrease the planar size of the ground plane even further than the previous 4x4 case. To do so, two different geometries for the ground plane are proposed as shown in Fig. 4.27. The size of the square patches is the same as the one designed in section 4.2. The upper and lower dielectric slab have equal heights of 1.5748mm with a planar size of $0.438\lambda_0 \times 0.438\lambda_0$. The difference between these two proposed ground planes is the size of the PEC metal sheet backing their lower dielectric slab. The dimension of the larger ground plane, shown in Fig. 4.27a, is $0.836\lambda_0 \times 0.836\lambda_0$, whereas that of the smaller one, depicted in Fig. 4.27b, is $0.438\lambda_0 \times 0.438\lambda_0$.

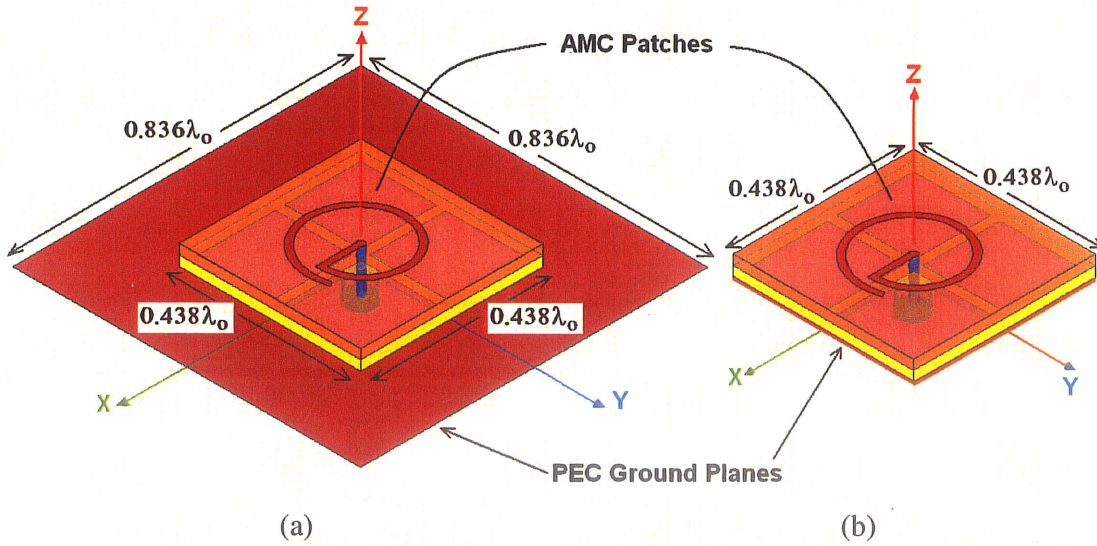


Fig. 4.27: 3-D view of the curl antenna over the AMC ground plane of 2x2 array of square patches over a dielectric slab with planar size of $0.438\lambda_0 \times 0.438\lambda_0$ backed by a metal sheet of size (a) large PEC ground of $0.836\lambda_0 \times 0.836\lambda_0$ (b) small PEC ground of $0.438\lambda_0 \times 0.438\lambda_0$ at $f=4.5\text{GHz}$.

Two parametric studies are carried out in terms of the number of turns and the curl constant for both the large and small ground planes. Figure 4.28 shows the axial ratio of the antennas shown in Fig. 4.27 versus the number of turns, when $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$, and $f=4.5\text{GHz}$ at the boresight direction. The minimum axial ratio of 10dB is obtained. That means the antenna radiation is far off from the circular polarization. The second parametric study in terms of the curl constant is shown in Fig. 4.29, when $n=1.07253$ turns, $D_{\text{edge}}=1.55\text{mm}$, and $f=4.5\text{GHz}$ at the boresight direction. Although, the axial ratio is not sensitive to the curl constant, no improvement in the axial ratio is observed. It is concluded that reducing the number of patches from 4×4 array to 2×2 array deteriorates the CP performance of the curl. In addition, the larger metal sheet does not improve the axial ratio of the antenna.

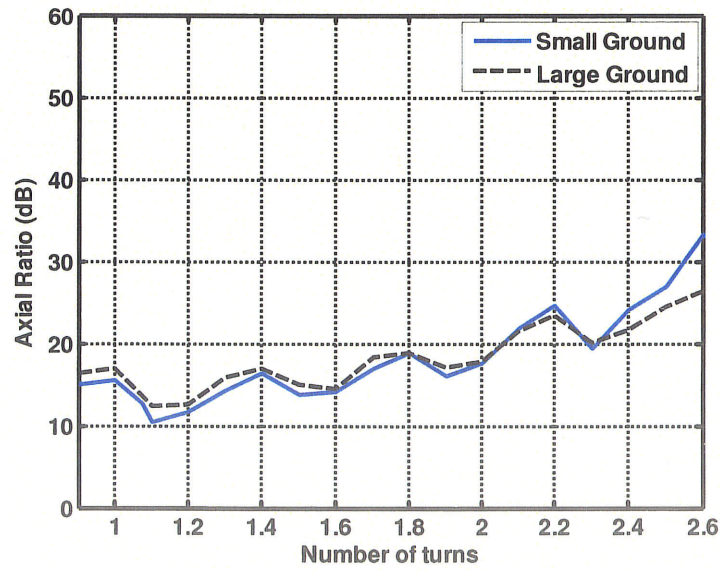


Fig. 4.28: Axial ratios of the antennas shown in Fig. 4.27 versus number of turns at $\theta=0^\circ$, when $a=0.3375\text{mm/rad}$, $D_{\text{edge}}=1.55\text{mm}$, and $f=4.5\text{GHz}$.

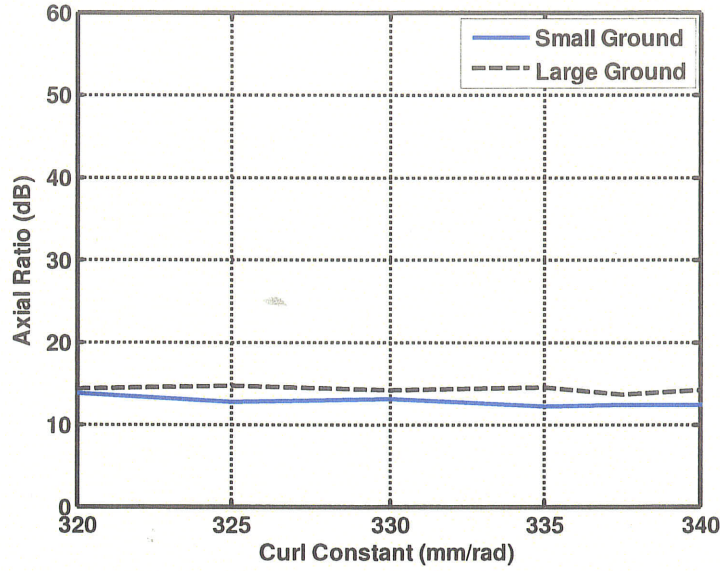


Fig. 4.29: Axial ratios of the antennas shown in Fig. 4.27 versus curl constant, when $n=1.07253$ turns, $D_{\text{edge}}=1.55\text{mm}$, and $f=4.5\text{GHz}$.

4.5 Summary

In this chapter, several parametric studies of a curl antenna over an AMC ground plane were conducted using the HFSS v10.1. The impact of the curl constant “a”, the number of turns “n”, the edge distance “ D_{edge} ”, and the offset feeding on the axial ratio were studied. The proposed AMC ground plane consisted of planar arrays of square patches with no vertical vias. In order to have a physically robust structure, the curl antenna was etched on a dielectric layer over the AMC patches. First, an AMC surface made of a 4×4 array of square patches was considered as the ground plane. The best axial ratio was obtained when $a = 0.3375\text{mm/rad}$ and $n=1.07253$ turns and $D_{\text{edge}}=1.55\text{mm}$. The antenna height, h_2 , was reduced to $0.02\lambda_0$, at the center operating frequency of 4.5GHz . In addition, the planar size of the antenna AMC ground was just $0.836\lambda_0 \times 0.836\lambda_0$. Therefore, a very small and low profile antenna was developed in order to generate right-

hand circularly polarized waves with the axial ratio of 0.25dB at the boresight angle, $\theta = 0^\circ$. The 3dB beamwidth occurred over the observation angles of $-30^\circ \leq \theta \leq +30^\circ$. The RHCP gain of this low-profile antenna was 8dBi. It was found that the radial linear part of the curl antenna over the AMC ground plane had profound impact on its CP performance, in contrast to the case of the curl antenna over a traditional PEC ground plane. Without the radial linear part, the optimum axial ratio was obtained at the frequency of 4.8GHz. Extending the curl toward its center moved the frequency back to 4.5GHz.

The curl antenna over an AMC surface with 2×2 array of square patches with two different metal sheet sizes was also investigated. Studies of the axial ratio in terms of the number of turns and the curl constant showed that the reduction of the number of AMC patches deteriorate its CP performance, even if the 2×2 array of square patches were backed with a larger PEC ground plane.

Chapter 5

Experimental Studies

5.1 Introduction

To verify the simulation results given in the previous chapter, the optimum case was selected to be fabricated and studied experimentally. This case is a low-profile curl antenna over an AMC ground plane with no vertical vias. The curl antenna was fed at its center and had designed parameters of $\alpha_{st}=6\pi$, $n=1.07253$ turns and $a=0.3375\text{mm/rad}$, given in Table 4.1. The planar size of the entire structure was $0.836\lambda_0 \times 0.836\lambda_0$ and the curl antenna was placed on a dielectric layer, having a thickness of $0.02\lambda_0(1.5748\text{mm})$ on top of the AMC ground plane, where λ_0 is the wavelength of the free space at the frequency of 4.5GHz, Fig.4.3.

As described in chapter four, this antenna was to be fabricated over a dielectric layer, instead of being suspended in the air, to produce a robust structure. This substrate was then placed over the AMC ground plane. In practice, if the dielectric layer was not bonded to the AMC surface, there may be an air-gap between these two layers in the fabrication process. This air-gap will, in turn, change the center operating frequency of the antenna as will be shown in this chapter. The experimental results are given and compared with the simulated ones.

5.2 An Overview of CP Measurement Method

The standard method to measure the axial ratio and CP gain of an antenna using a rotating linear transmitter has been studied in [41]. Figure 5.1 shows the typical measured CP patterns of an antenna under test (AUT). The level of axial ratio is equal to the depth

of the null at each observation angle as illustrated in Fig. 5.1 and it is given by the following equation:

$$AR(dB) = 20 \log_{10} \left(\frac{1+e}{1-e} \right) \quad (5.1)$$

where $e = 10^{-(P_{dB}/20)}$ and P_{dB} is the absolute value of the ripple at each angle.

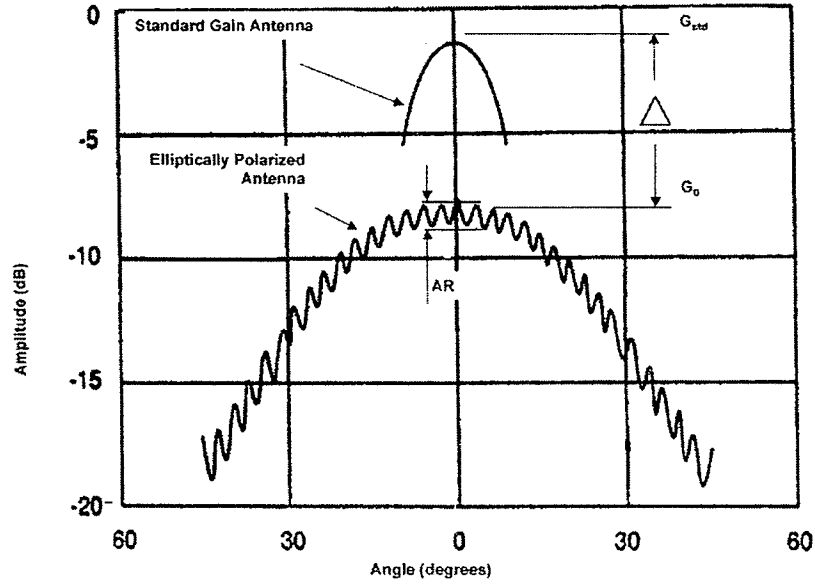


Fig. 5.1: A typical measured CP radiation pattern of an antenna [41], using a rotating linear transmitter.

Moreover, the gain can be easily found by using a substitution technique which employs a linearly-polarized standard gain antenna replaced with the AUT. Therefore, the CP gain of the AUT may be calculated by the following equation [41]:

$$G_{AUT}(dBic) = G_{std} - \Delta + G_C + 3 \quad (5.2)$$

where G_{std} represents the gain of the standard antenna and Δ represents the difference between the measured power levels of the standard and test antennas, as shown in Fig. 5.1. Also, G_C , given by Eq.5.3, is the correction factor due to elliptically polarized fields

of the AUT. This is because of the fact that antennas cannot produce pure CP field in practice.

$$G_c(dB) = 20 \log_{10}[0.5(1 + 10^{-AR/20})] \quad (5.3)$$

5.3 Curl Antenna Measurement Results

The fabricated low-profile curl antenna over an AMC ground plane is shown in Fig.5.2. This antenna is selected based on the center-fed optimum case which was designed and simulated in section 4.3.3. The curl antenna parameters are $\alpha_{st}=6\pi$, $n=1.07253$ turns and $a=0.3375\text{mm/rad}$. The planar size of the entire structure is $0.836\lambda_0 \times 0.836\lambda_0$ and the curl antenna is placed at a distance of $0.02\lambda_0$ from the top of the AMC ground plane, where λ_0 is the wavelength of the free space at the frequency of 4.5GHz.

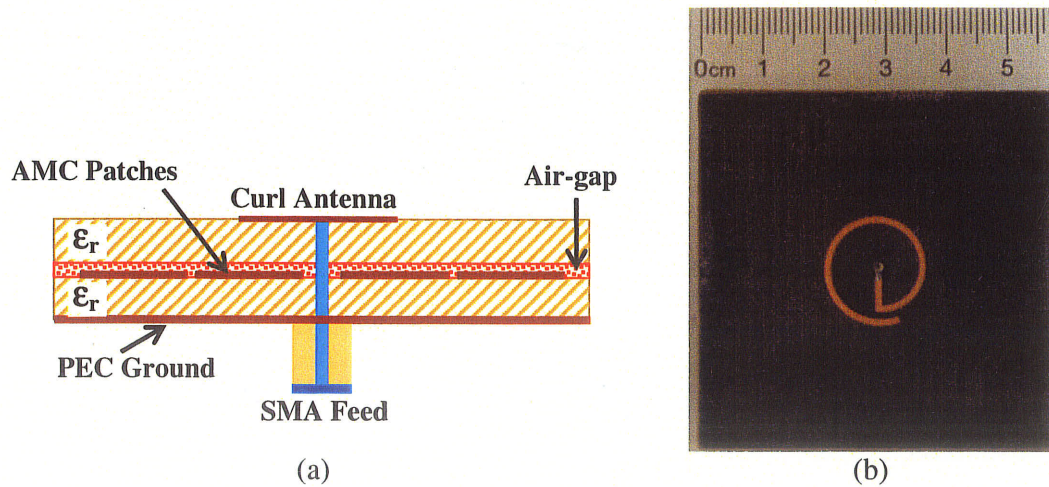


Fig. 5.2: (a) cross-section view of the experimental model showing an air-gap between the upper dielectric layer and the AMC surface (b) the top-view photo of the fabricated low-profile curl antenna.

The antenna is tested in the Antenna Lab at the University of Manitoba over a frequency range of 4GHz to 5.5GHz. The available measurement setup automatically

calculates the axial ratio and CP gain of the antenna under test (AUT). The measured CP radiation patterns at the frequency of 4.5GHz is shown in Fig. 5.3. Around the boresight direction, the measured CP gain was 8.93dBic with an axial ratio of 5.94dB. This experimental axial ratio differs considerably from the simulated one. Consequently, the geometric differences between the simulated and measured antennas were studied. The main difference was in the air-gap, between the upper dielectric layer and the AMC surface, in the experimental model. This air-gap was caused by not bonding the two surfaces and placing one over the other, using nylon screws, as shown in Fig. 5.2a.

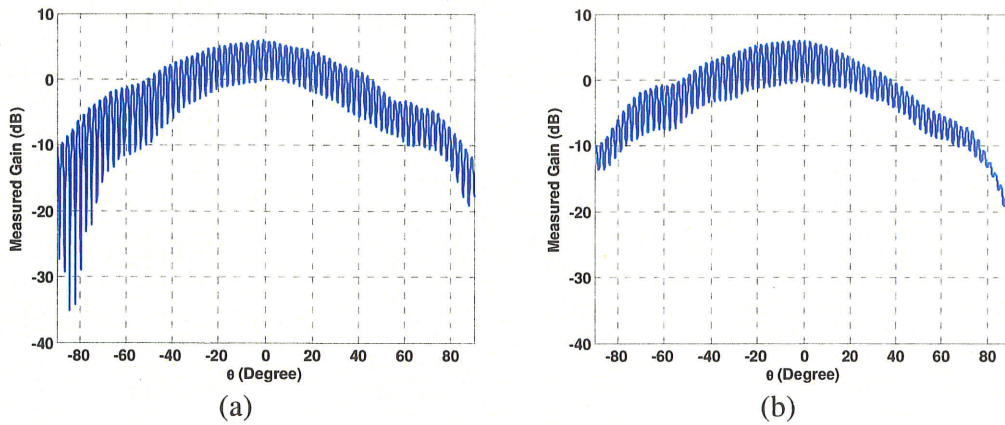


Fig. 5.3: Measured CP radiation patterns of the antenna shown in Fig. 5.2 at $f=4.5\text{GHz}$, (a) $\phi=0^\circ$ (b) $\phi=90^\circ$ planes.

To better understand the difference between the measured and simulated results at the frequency of 4.5GHz, it is important to study the effect of the air-gap between the dielectric layer and AMC surface. The existence of an air-gap occurs as a result of the fabrication process, as well as, the imperfections of the dielectric layers such as the non-uniform thickness and non-flatness. The impact of the air-gap on the antenna axial ratio is shown in Fig. 5.4, which is obtained by the HFSS v10.1. The frequency for the optimum

axial ratio has a direct relationship with the size of the air-gap, as illustrated in Fig. 5.4. As can be seen, the frequency is moved from 4.5GHz to 4.8GHz as the air-gap size changes from zero to 0.1mm. To find the frequency shift due to the air-gap, Table 5.1 compares the axial ratios obtained from the measured and simulated values with an air-gap size of 0.1mm at the boresight angle over the 4.0-5.0GHz frequency range. Table 5.1 demonstrates a concurrence between the measured and simulated results at the frequency of 4.8GHz. This study shows that even a small air-gap can alter the frequency at which the optimum axial ratio is achieved.

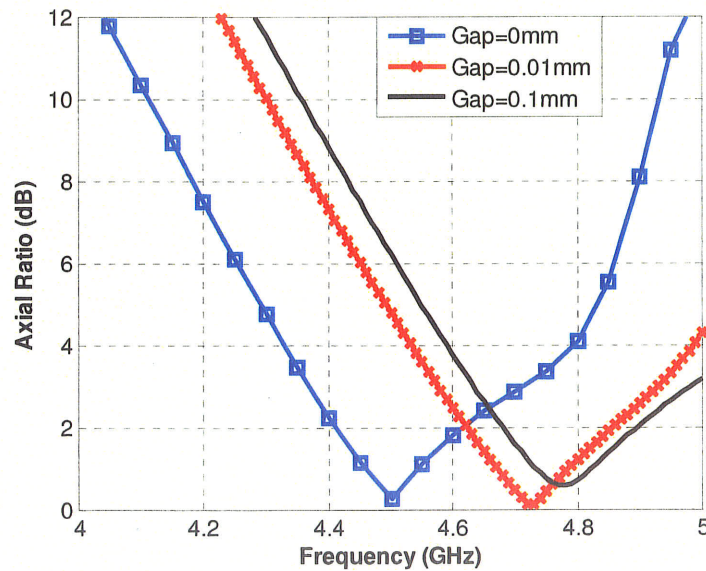


Fig. 5.4: The simulated boresight axial ratios of the optimum curl antenna for different air-gap sizes for the experimental antenna of Table 4.1.

Table 5.1: Comparison of the axial ratios obtained from measurement and simulation with an air-gap of 0.1mm at $\theta=0^\circ$, for the experimental antenna of Table 4.1.

Frequency (GHz)	Measured AR(dB)	Simulated AR(dB) Air-gap=0.1mm
4.0	4.77	20.09
4.1	16.61	17.15
4.2	12.21	14.30
4.3	11.04	11.53
4.4	9.07	8.83
4.5	5.94	6.23
4.6	3.41	3.78
4.7	1.83	1.60
4.8	0.68	0.72
4.9	1.74	2.05
5.0	1.11	3.19

Figure 5.5 presents the simulated and measured axial ratios of the low-profile curl antenna of Table 4.1 at different ϕ -planes. The simulation results were obtained for the prototype with an air-gap of 0.1mm at the frequency of 4.8GHz, as shown in Table 5.1. The results agree with each other, and adhere to the same trend over the observation angles of $-60^\circ \leq \theta \leq +60^\circ$.

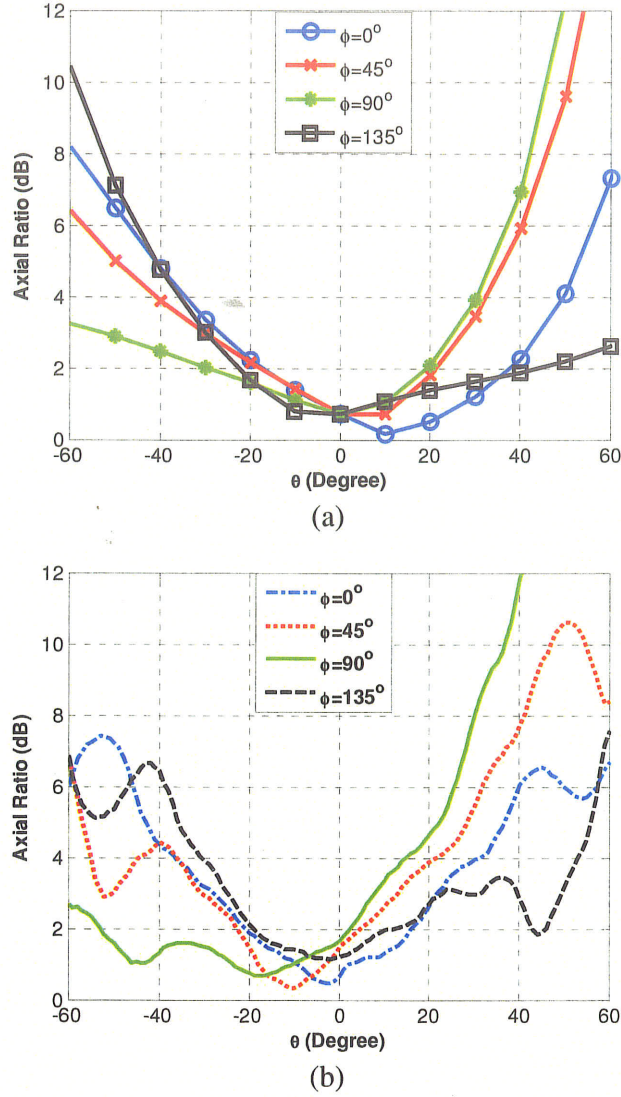


Fig. 5.5: The (a) simulated and (b) measured axial ratios of the low profile curl antenna of Table 4.1 over the AMC ground plane with an air-gap of 0.1mm at $f=4.8\text{GHz}$.

Finally, figures 5.6 and 5.7 give the simulated and measured CP radiation pattern at the frequency of 4.8GHz, respectively. The measured CP gain is 6.21dBic, whereas the simulated one is about 8dBic at the boresight direction. The small ripples, shown in Fig. 5.7, also confirm the good CP performance of the antenna around its main beam.

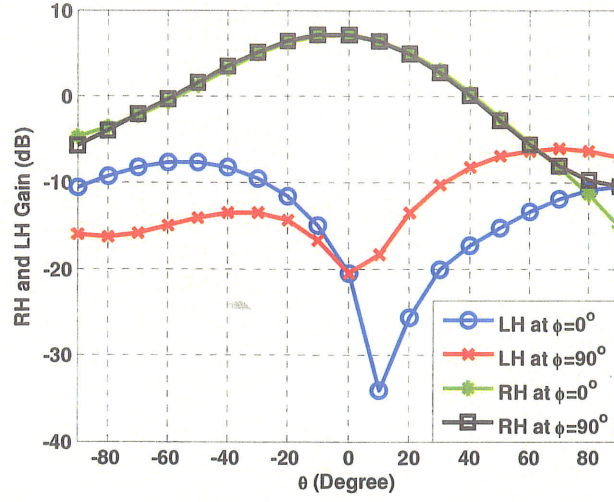


Fig. 5.6: The simulated CP radiation patterns of the low profile curl antenna of Table 4.1 over the AMC ground plane with an air-gap of 0.1mm at $f=4.8\text{GHz}$.

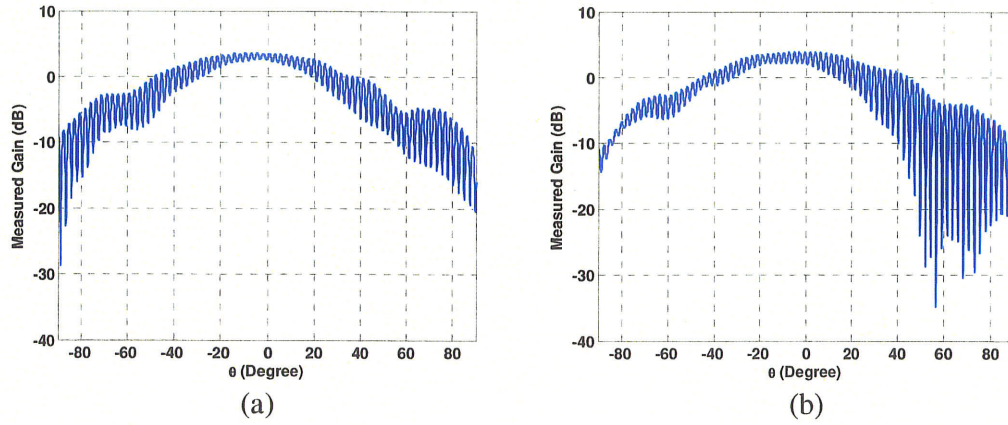


Fig. 5.7: The measured CP radiation patterns of the low profile curl antenna of Table 4.1 over the AMC ground plane with an air-gap of 0.1mm at $f=4.8\text{GHz}$, (a) $\phi=0^\circ$ (b) $\phi=90^\circ$ planes.

5.4 Summary

In this chapter, the low-profile curl antenna over an AMC ground plane with the optimum parameters, which was designed and simulated using the HFSS v10.1 in chapter four and shown in Table 4.1, was chosen for measurement. As shown in chapter four, two optimized low-profile curl antennas were developed. One antenna was probe fed at the center, and the other was fed off center, on the spiral. To simplify the fabrication process, the center-fed curl antenna was selected. The axial ratio and CP gain of this antenna were measured in the Antenna Lab at the University of Manitoba over a frequency range of 4.0-5.5GHz. In the experimental model, a frequency shift was observed. Subsequently, and to explain the reason for the frequency shift, the impact of the air-gap size between the two substrate layers was investigated. The simulation results showed that the existence of the air-gap increased the frequency at which the minimum axial ratio was obtained.

With an air-gap size of 0.1mm the simulated results agreed well with experiment and the frequency for minimum axial ratio increased from 4.5GHz to 4.8GHz. These results showed the importance of the air-gap between the planar dielectric layer and the AMC surface. They also confirmed the validity of the simulated data.

Chapter 6

Dual-Arm Spiral Antenna over an AMC Surface

6.1 Introduction

In this chapter, dual-arm Archimedean spiral antennas are studied over both PEC and AMC ground planes. The curl antenna which is a single-arm spiral was investigated over both PEC and AMC ground planes in chapter three and four, respectively, and a low-profile curl antenna was developed over an AMC ground plane. Single-arm and dual-arm spirals are conceptually very similar to each other. However, a dual-arm spiral exhibits better performance than its single-arm counterpart. In this chapter, first a balanced fed dual-arm spiral antenna will be studied over a PEC ground plane. The optimum designed curl parameters of chapter three are used to tune the dual-arm antenna. Then, a low-profile dual-arm spiral is investigated over an AMC ground plane using the optimum parameters obtained in chapter four at the same height of $0.02\lambda_0$. The dual-arm spiral antenna shows a more symmetric CP pattern than a single-arm one, due to its symmetrical geometry. Numerical results, obtained by the Finite Element based software HFSS v10.1, are presented. The center operating frequency is 4.5GHz.

6.2 Dual-Arm Archimedean Spiral Antenna over an Infinite PEC Ground Plane

Spiral antennas provide good CP performance over a wide beamwidth, which are required in many applications like GPS, spread spectrum and multifunction radio frequency systems. They are also used in broadband wireless applications. A dual-arm spiral antenna has both electrically and physically symmetric structure, when it is excited

by a balanced feed. This feed must provide outputs with proper phase differences over the same or greater frequency bandwidth as the antenna. In this work, a balanced feed model is used for the simulation of the antenna. The fundamental mode of the dual-arm spiral antenna is when the circumference is approximately one wavelength similar to the curl antenna. This mode has a peak at the broadside direction with a wide beamwidth.

Here, the performance of a dual-arm Archimedean spiral is shown when it is placed over a PEC ground plane at the height of $\lambda_0/4$, as was done for a curl antenna in chapter three. The geometry of a dual-arm spiral is shown in Fig. 6.1.

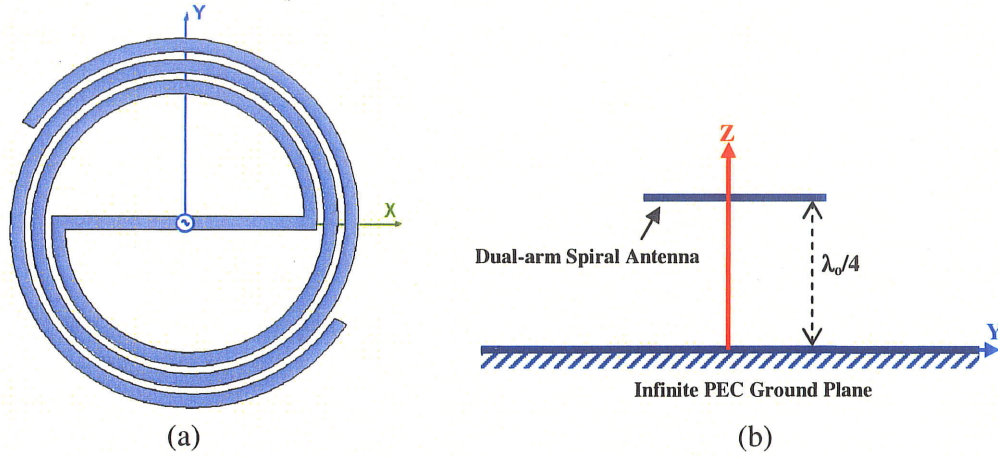


Fig. 6.1: (a) Top-view (b) cross-section view of a dual-arm Archimedean spiral antenna over an infinite PEC ground plane.

To study the CP performance of the dual-arm spiral antenna over an infinite PEC ground plane, the optimized values found in chapter three are used. They are $\alpha_{st}=6\pi$, $a=0.485\text{mm/rad}$, $n=1.45$, and $h=16.67\text{mm}=\lambda_0/4$. The dual-arm spiral antenna is placed over an infinite PEC ground plane at a distance of $\lambda_0/4$, as discussed in chapter three. First, the spiral constant “a” remains unchanged and the effect of “n” on the axial ratio is studied. Table 6.1 summarizes these results. As observed, the case of $n=1.42$ gives the lowest axial ratio at the center operating frequency of 4.5GHz.

Table 6.1: Axial ratios of the dual-arm spiral antenna over an infinite PEC ground plane, when $\alpha_{st}=6\pi$, $a=0.485\text{mm/rad}$, $h=16.67\text{mm}$, and $f=4.25\text{GHz}$, 4.5GHz , 4.75GHz at $\theta=0^\circ$.

Number of turns “n”	AR(dB)@4.25GHz	AR(dB)@4.50GHz	AR(dB)@4.75GHz
1.25	2.65	4.39	6.00
1.35	1.49	3.03	3.22
1.41	0.96	1.35	3.47
1.42	0.59	1.29	3.92
1.43	0.62	1.34	4.00
1.45	0.70	2.19	5.45
1.47	0.96	2.85	6.25
1.50	2.00	4.35	7.96

Now, the impact of the spiral constant is studied on the axial ratio for the above case of $n=1.42$, while the other parameters are unchanged. The results are shown in Table 6.2.

Table 6.2: Axial ratios of the dual-arm spiral antenna over an infinite PEC ground plane, when $\alpha_{st}=6\pi$, $n=1.42$, $h=16.67\text{mm}$, and $f=4.25\text{GHz}$, 4.50GHz , 4.75GHz at $\theta=0^\circ$.

Spiral constant “a”	AR(dB)@4.25GHz	AR(dB)@4.50GHz	AR(dB)@4.75GHz
0.445	2.04	0.52	1.03
0.450	2.08	0.43	1.52
0.455	1.18	0.20	1.66
0.460	1.12	0.31	2.12
0.470	0.99	0.47	2.31
0.485	0.59	1.30	3.92

As a result, the optimum parameters of the dual-arm spiral antenna, over an infinite PEC ground plane, are given in Table 6.3 at the center operating frequency of 4.5GHz.

Table 6.3: The optimum parameters of the dual-arm spiral antenna over an infinite PEC ground plane at the center operating frequency of 4.5GHz.

Curl constant “a” (mm/rad)	0.455
Number of turns “n”	1.42
α_{st}(radians)	6π
Height “h” (mm)	$16.67=\lambda_o/4$

The resulting axial ratios for the optimum design are shown in Fig. 6.2 at different ϕ -planes. As can be seen, the axial ratio has a 3dB beamwidth over the observation angles of $-50^\circ \leq \theta \leq +50^\circ$. Also, all results show the symmetric behavior over the entire observation angles, whereas the axial ratio of the single spiral curl antenna was not symmetric, and it had a smaller 3dB axial ratio beamwidth of $-35^\circ \leq \theta \leq +25^\circ$. This is a remarkable feature of a dual-arm spiral antenna, when compared to a curl antenna, over a PEC ground plane.

To show the frequency behavior of the above optimum case, Fig. 6.3 depicts the axial ratios at two different frequencies of 4.25GHz and 4.75GHz. The axial ratio is increased to about 1.25dB and 2dB at the frequency of 4.25GHz and 4.75GHz, respectively, at the boresight angle. However, they still exhibit good CP performance with 3dB beamwidths of $-50^\circ \leq \theta \leq +45^\circ$ and $-40^\circ \leq \theta \leq +40^\circ$ at the frequency of 4.25GHz and 4.75GHz, respectively.

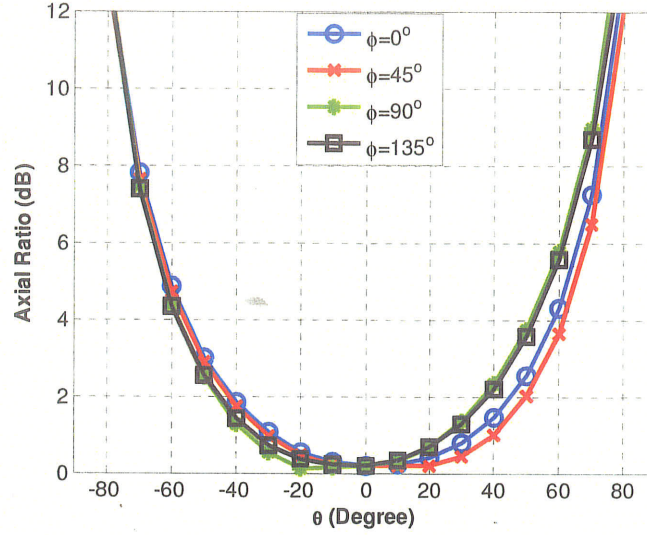


Fig. 6.2: Axial ratio of the dual-arm spiral antenna over an infinite PEC ground plane, when $\alpha_{st} = 6\pi$, $n=1.42$, $a = 0.455\text{mm/rad}$, $h = 16.67\text{mm} = \lambda_0/4$, and $f = 4.5\text{GHz}$ at different ϕ -planes.

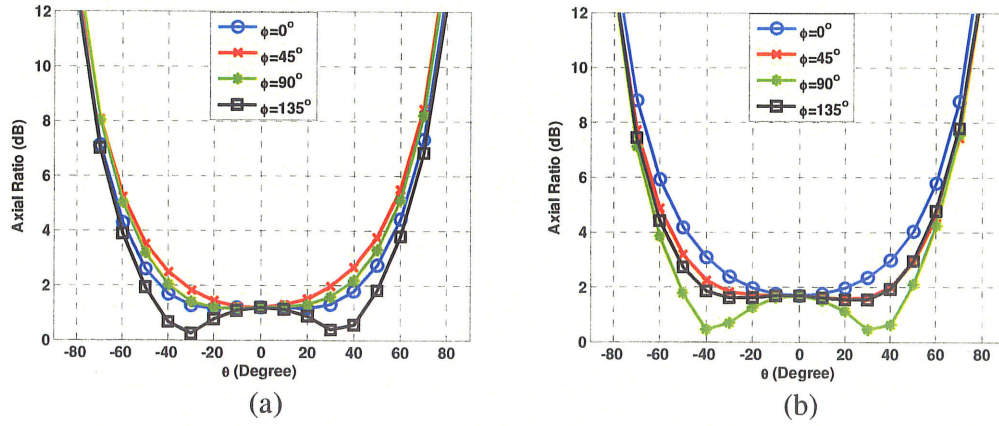
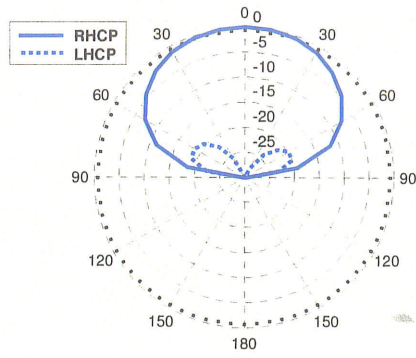
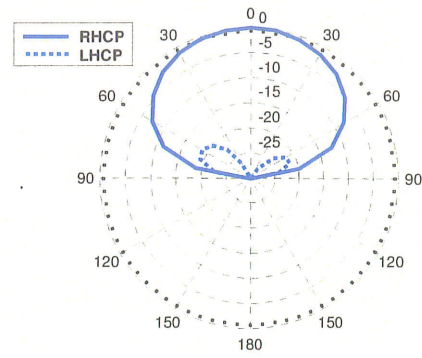


Fig. 6.3: Axial ratio of the dual-arm spiral antenna over an infinite PEC ground plane, when $\alpha_{st} = 6\pi$, $n = 1.42$, $a = 0.455\text{mm/rad}$, $h = 16.67\text{mm} = \lambda_0/4$, and (a) $f = 4.25\text{GHz}$ and (b) $f = 4.75\text{GHz}$ at different ϕ -planes.

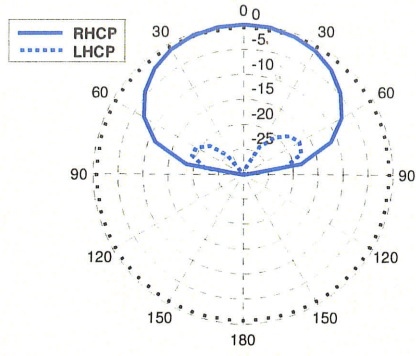
Figure 6.4 illustrates the normalized RHCP and LHCP radiation patterns of the dual-arm spiral antenna over an infinite PEC ground planes at ϕ equal to 0° , 45° , 90° , and 135° . Again, all demonstrate good symmetric patterns with a dominant RHCP polarization.



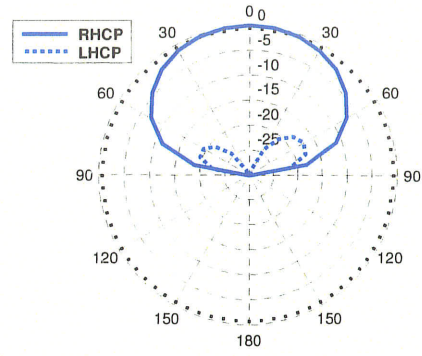
(a)



(b)



(c)



(d)

Fig. 6.4: Normalized radiation patterns of the dual-arm spiral antenna over an infinite PEC ground plane, when $\alpha_{st}=6\pi$, $n=1.42$, $a=0.455\text{mm/rad}$, and $h=16.67\text{mm}=\lambda_0/4$ for different ϕ planes : (a) $\phi=0^\circ$ (b) $\phi=45^\circ$ (c) $\phi=90^\circ$ (d) $\phi=135^\circ$ at $f=4.5\text{GHz}$.

The RH and LH gain patterns of the antenna under study are shown in Fig. 6.5, at the principle planes. The maximum RH gain of 8.6dBic is obtained at the broadside direction, with a wide beamwidth. The level of LH component, i.e. the cross polarization, is well below -20dB around the boresight angle.

The frequency behavior of the axial ratio for both dual-arm spiral and curl antenna placed over an infinite PEC ground plane is compared in Fig. 6.6. The 3dB frequency bandwidth of the dual-arm spiral is slightly wider than that of the curl antenna.

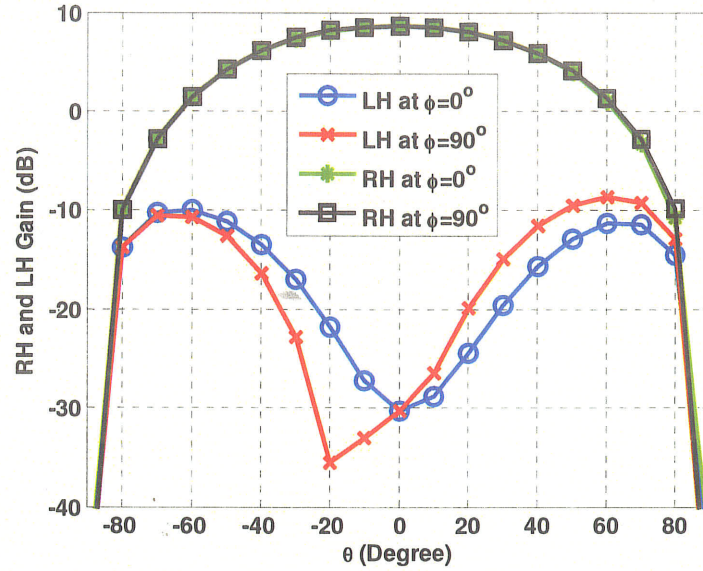


Fig. 6.5: Right-Hand and Left-Hand gains of the dual-arm spiral antenna over an infinite PEC ground plane, when $\alpha_{st}=6\pi$, $n=1.42$, $a=0.455\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$, and $f=4.5\text{GHz}$ at principle planes.

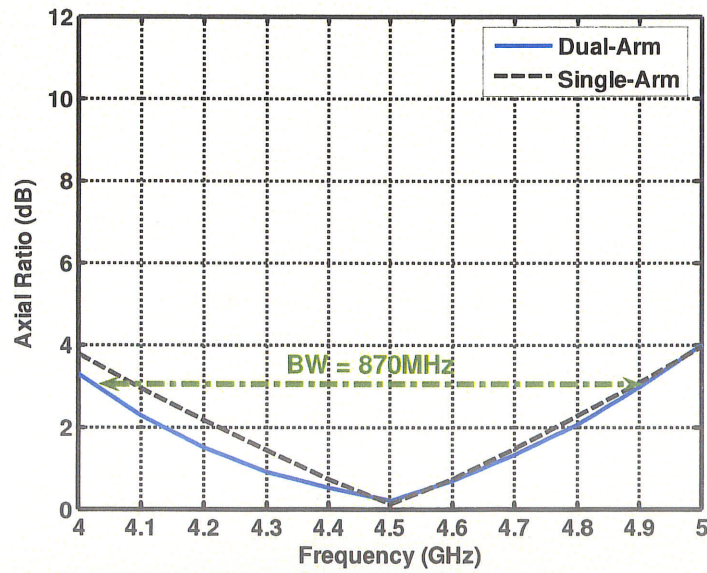


Fig. 6.6: The frequency behavior of the axial ratio for dual-arm spiral antenna ($\alpha_{st}=6\pi$, $n=1.42$, $a=0.455\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$) and curl antenna of chapter three ($\alpha_{st}=6\pi$, $n=1.45$, $a=0.485\text{mm/rad}$, $h=16.67\text{mm}=\lambda_0/4$), over an infinite PEC ground plane at $\theta=0^\circ$.

Finally, the surface current distributions for the radial linear and spiral parts of the optimum designed dual-arm spiral antenna over an infinite PEC ground plane are shown in Fig.6.7 at the center frequency of 4.5GHz. As expected, the current magnitude goes to zero as the waves travel toward each arm of the spiral antenna.

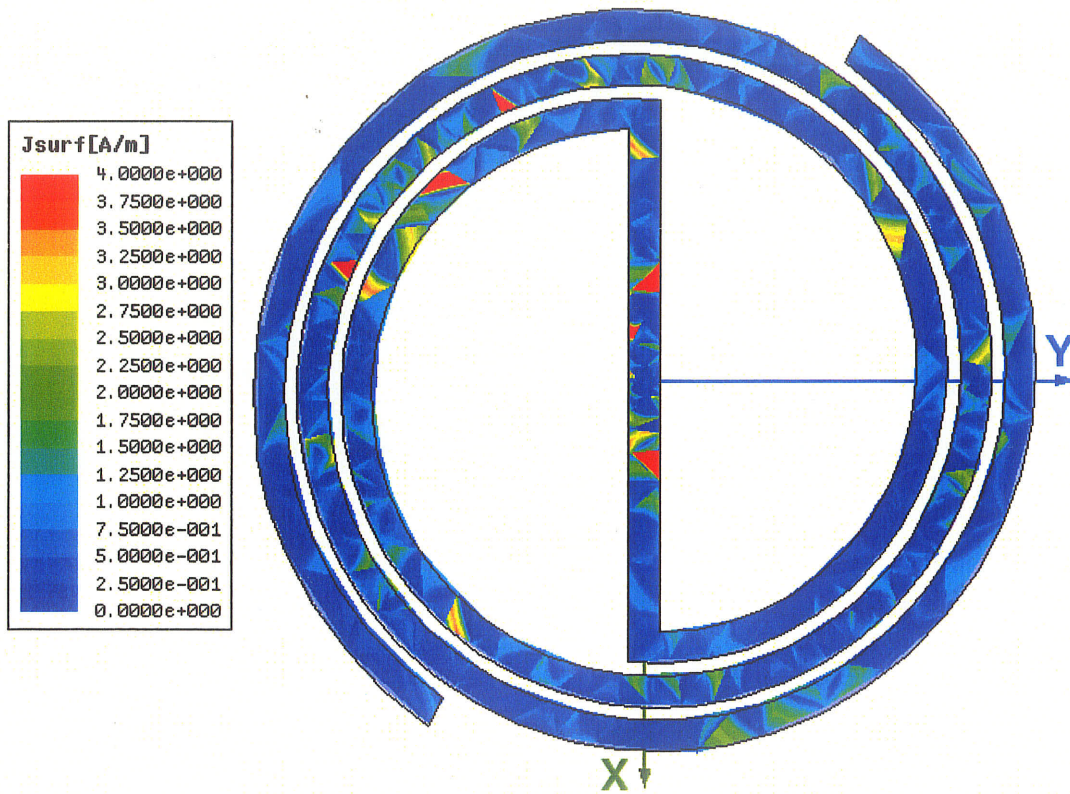


Fig. 6.7: The surface current distribution over radial linear and curved sections of the dual-arm spiral antenna over an infinite PEC ground plane with $n=1.42$ turns, $a=0.455\text{mm/rad}$, and $h=16.67\text{mm}=\lambda_0/4$, at $f=4.5\text{GHz}$.

6.3 Dual-arm Archimedean Spiral antenna over an AMC Ground plane

In this section, a low-profile dual-arm spiral antenna is studied over the AMC ground plane used in chapter four, section 4.3.3, at the center operating frequency of 4.5GHz. The main goal is to tune the dual-arm spiral antenna over this artificial magnetic ground plane at the same distance of $0.02\lambda_0$ as for the curl antenna. The geometry of the antenna is shown in Fig. 6.8.

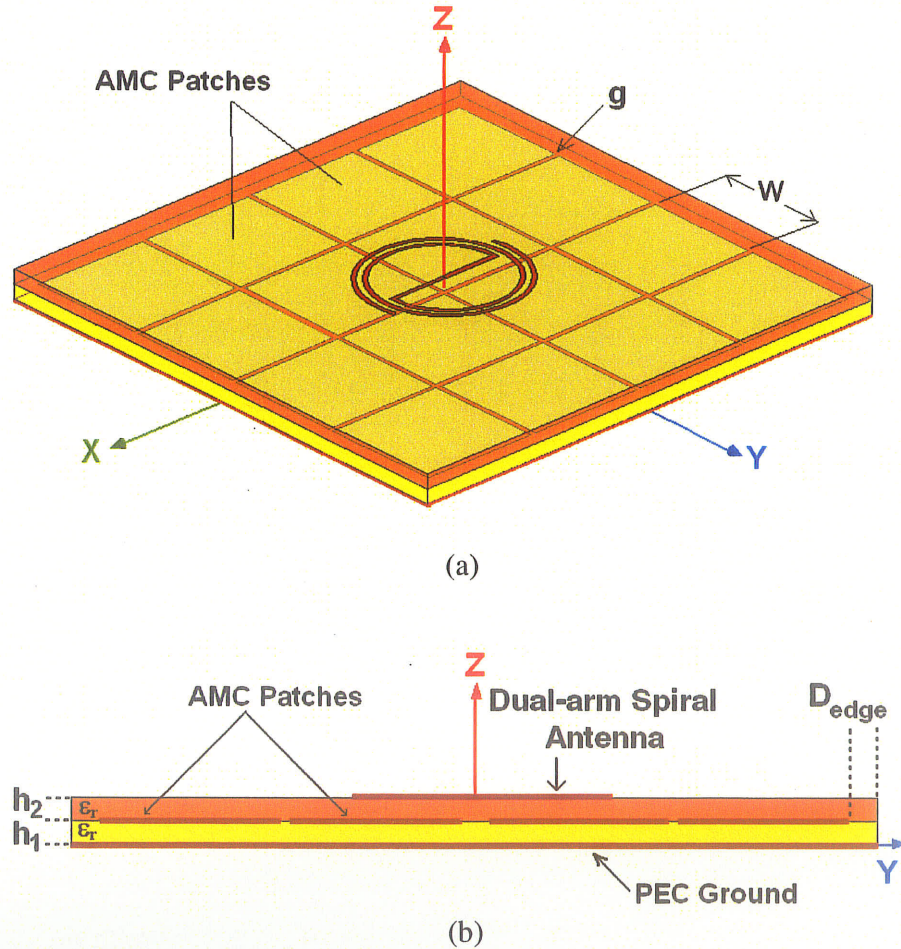


Fig. 6.8: (a) Top view (b) cross-section view of the geometry of the dual-arm spiral antenna over an AMC ground plane consisting of a 4x4 array of square patches with $w=12.8\text{mm}$, $g=0.5\text{mm}$, $\epsilon_r=2.5$, and $D_{edge}=1.55\text{mm}$.

The optimized curl parameters, given in Table 4.1, are $\alpha_{st}=6\pi$, $a=0.3375\text{mm/rad}$, $n=1.07253$ turns. Similar to the previous section, first the spiral constant remains unchanged and the effect of the number of turns on the axial ratio is studied. The simulation results are given in Table 6.4 at the center operating frequency of 4.5GHz and the boresight direction.

Table 6.4: Axial ratios of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8, when $\alpha_{st}=6\pi$, $a=0.3375\text{mm/rad}$, and $f=4.25\text{GHz}$, 4.5GHz , 4.75GHz at $\theta=0^\circ$.

Number of turns “n”	AR(dB)@4.25GHz	AR(dB)@4.50GHz	AR(dB)@4.75GHz
1.0	8.95	3.97	1.90
1.02	8.56	2.94	2.87
1.05034	7.20	2.08	4.67
1.07253	6.24	2.98	5.96
1.08	5.78	3.43	6.40
1.10	4.63	4.91	7.53

As can be seen in the above table, the lowest axial ratio occurs at the center operating frequency of 4.5GHz when “n” is equal to 1.05034 turns for $a=0.3375\text{mm/rad}$. Now, further tuning is done by changing the spiral constant with a fixed number of turns of 1.05034. These results are shown in Table 6.5.

Table 6.5: Axial ratios of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8, when $\alpha_{st}=6\pi$, $n=1.05034$, at $f = 4.25\text{GHz}$, 4.5GHz , and 4.75GHz at $\theta=0^\circ$.

Spiral constant "a"(mm/rad)	AR(dB)@4.25GHz	AR(dB)@4.50GHz	AR(dB)@4.75GHz
0.2700	6.18	0.63	5.41
0.2750	6.86	0.34	4.87
0.2800	6.56	0.26	4.91
0.2850	6.99	0.42	5.01
0.3115	7.47	1.35	4.63
0.3300	7.35	1.84	4.77
0.3375	7.20	2.08	4.67
0.3400	6.71	2.41	5.19

As can be seen, a minimum axial ratio of 0.26dB is obtained with a smaller spiral constant of 0.28mm/rad. This means that the dual-arm spiral antenna becomes smaller than the single-arm spiral antenna over an AMC ground plane. This is because of the proximity of the antenna to a resonant structure of the artificial magnetic ground plane. That is, a strong interaction between the antenna and the AMC ground plane will shrink the size of the dual-arm spiral antenna, compared to the single-arm spiral curl antenna over an AMC ground plane described in chapter four. Table 6.6 compares the single-arm and dual-arm spiral antenna parameters over the AMC ground plane. As can be seen, the size of the dual-arm spiral antenna is at least 17% smaller than that of single-arm spiral antenna.

Table 6.6: The optimum parameters of the single-arm and dual-arm spiral antennas over the AMC ground plane at $f=4.5\text{GHz}$ and $h_1=h_2=1.5748\text{mm}=0.02\lambda_0$.

	Single-arm	Dual-arm
Curl constant “a” (mm/rad)	0.3375	0.28
Number of turns “n”	1.07253	1.05034

As a result, the optimized parameters of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8 are given in Table 6.7 at the center operating frequency of 4.5GHz.

Table 6.7: The optimum parameters of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8 at the center operating frequency of 4.5GHz.

Curl constant “a” (mm/rad)	0.28
Number of turns “n”	1.05034
$\alpha_{st}(\text{radians})$	6π
Height “h₂” (mm)	$1.5748=0.02\lambda_0$

It is recalled that this antenna is placed at a distance of $0.02\lambda_0$ over the AMC ground plane. Thus, the whole structure serves as a low-profile antenna. The axial ratio of the dual-arm spiral antenna for the above optimized parameters is illustrated in Fig. 6.9 at different ϕ -planes. All of them exhibit a great symmetry over the entire observation angles. It is interesting to note that the axial ratio of less than 3dB is obtained over $-90^\circ \leq \theta \leq +90^\circ$ at the principal planes, i.e., ϕ equal to 0° and 90° planes. The overall 3dB axial ratio beamwidth is, however, limited by the plane $\phi=135^\circ$ to $-45^\circ \leq \theta \leq +45^\circ$. To show the frequency behavior of the above optimum case, Fig. 6.10 depicts the axial ratios at

two different frequencies of 4.25GHz and 4.75GHz. The axial ratio is increased to about 6.5dB and 5dB at the frequency of 4.25GHz and 4.75GHz, respectively, at the boresight direction. The degradation in the axial ratio is due to the resonant structure of the AMC ground plane.

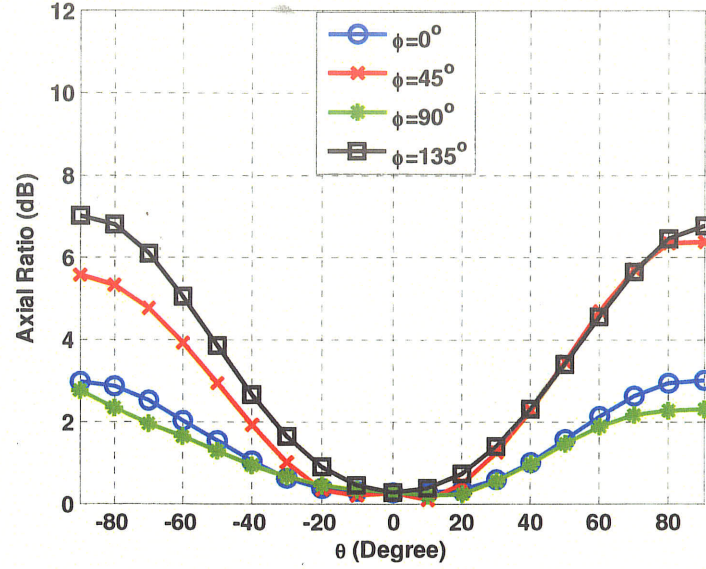


Fig. 6.9: Axial ratios of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8, when $\alpha_{st} = 6\pi$, $n = 1.05034$, $a = 0.28\text{mm/rad}$, and $f = 4.5\text{GHz}$ at different ϕ -planes.

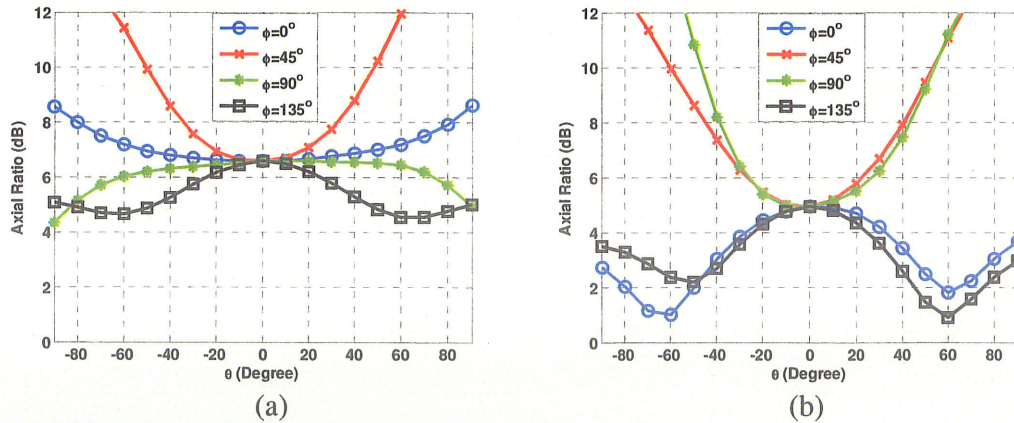


Fig. 6.10: Axial ratio of the dual-arm spiral antenna over an AMC ground plane shown in Fig. 6.8, when $\alpha_{st} = 6\pi$, $n = 1.05034$, $a = 0.28\text{mm/rad}$, and (a) $f = 4.25\text{GHz}$ and (b) $f = 4.75\text{GHz}$ at different ϕ -planes.

The normalized RHCP and LHCP radiation patterns of the dual-arm spiral antenna over the AMC ground plane, shown in Fig. 6.8, are depicted in Fig. 6.11 at ϕ equal to 0° , 45° , 90° , and 135° . As can be seen, the LHCP patterns, i.e. the cross polarizations, are almost negligible at principal planes, i.e., $\phi = 0^\circ$ and 90° , as their corresponding axial ratios are less than 3dB over the entire observation angles. The LHCP patterns are well below -20dB at the remaining planes. Perfect symmetric patterns are observed at all ϕ -planes.

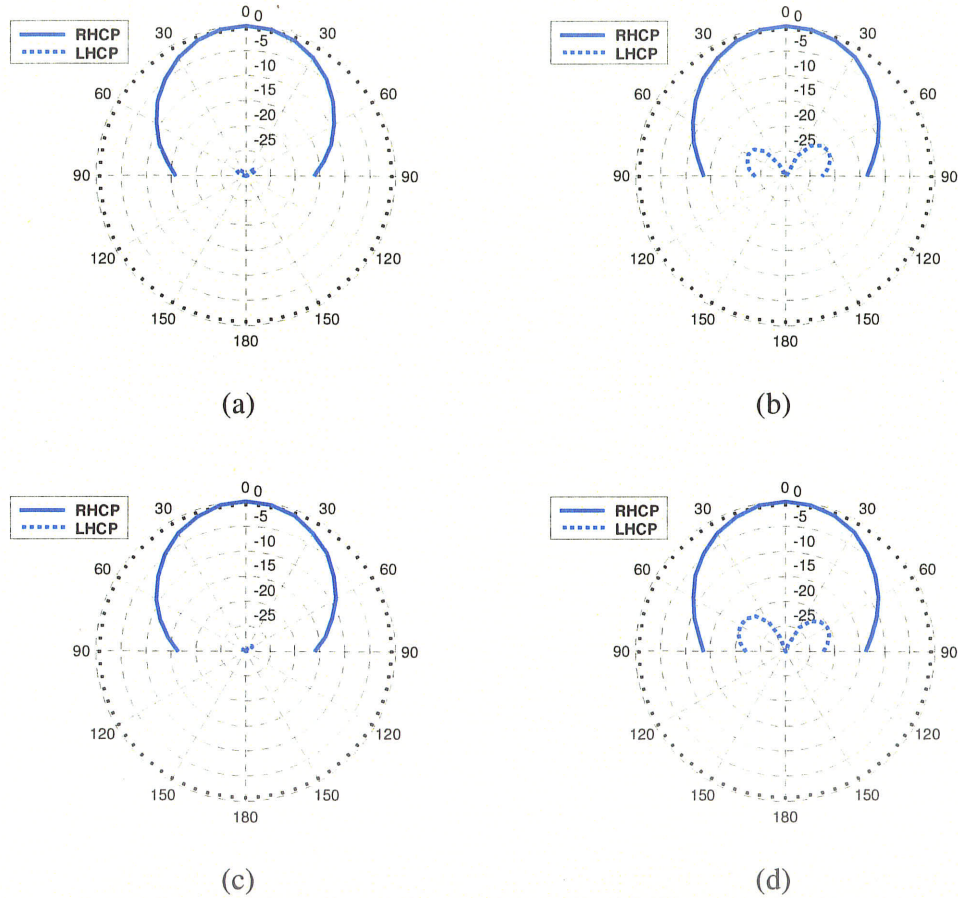


Fig. 6.11: Normalized radiation patterns of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8, when $\alpha_{st}=6\pi$, $n=1.05034$, and $a=0.28\text{mm/rad}$, for different ϕ planes : (a) $\phi=0^\circ$ (b) $\phi=45^\circ$ (c) $\phi=90^\circ$ (d) $\phi=135^\circ$ at $f=4.5\text{GHz}$.

The RH and LH gain patterns of the antenna under study are shown in Fig. 6.12 at the principle planes. The maximum RH gain of 8.97dBic is obtained at the broadside direction with a wide beamwidth. The level of the LH component, i.e. the cross polarization, is 35dB below the peak value of the RH one around the boresight direction. Finally, the frequency behaviors of the axial ratio for both dual-arm spiral and curl antenna placed over the AMC ground plane, shown in Fig. 6.8, are given in Fig. 6.13. The 3dB frequency bandwidth of the dual-arm spiral over the AMC is slightly narrower than that of the curl antenna over the AMC. This is because of the coupling between the dual-arm spiral and the AMC ground plane.

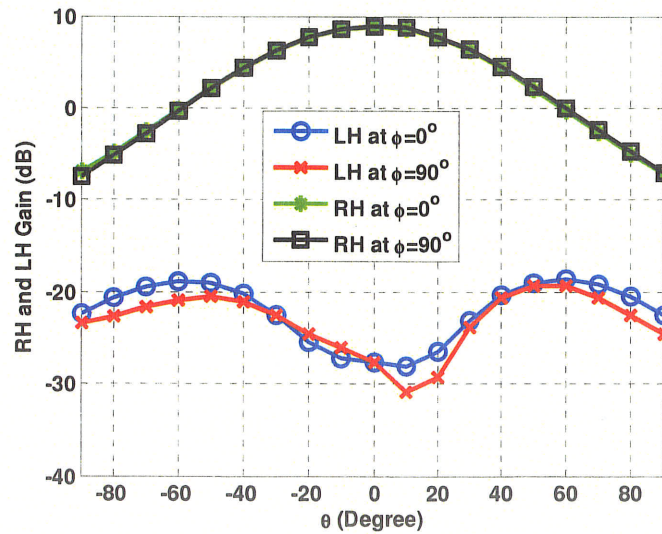


Fig. 6.12: Right-Hand and Left-Hand gains of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8, when $\alpha_{st}=6\pi$, $n=1.05034$, $a=0.28\text{mm/rad}$ and $f=4.5\text{GHz}$ at principle planes.

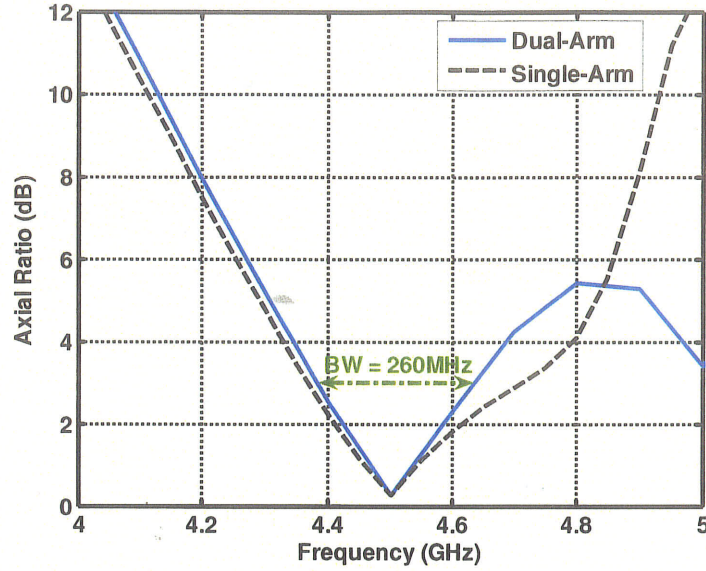


Fig. 6.13: The frequency behaviors of the axial ratios of the dual-arm spiral antenna ($\alpha_{st}=6\pi$, $n=1.05034$, $a=0.28\text{mm/rad}$) and the curl antenna of chapter four ($\alpha_{st}=6\pi$, $n=1.07253$, $a=0.3375\text{mm/rad}$) over the AMC ground plane shown in Fig. 6.6 at $\theta=0^\circ$.

The peak value of the RHCP gain of the dual-arm spiral antenna over both infinite PEC and finite AMC ground planes are compared in Fig. 6.14. The dual-arm spiral antenna has a gain variation of 2dB which is much less than that of the single-arm curl antenna over the AMC ground plane, as discussed in section 4.3.3. The dual-arm spiral antenna over the AMC ground plane has an almost flat RHCP gain over the frequency range of 4.4-4.9GHz. As for the PEC case, the gain response of the dual-arm spiral antenna is more flat than that of the single-arm spiral curl antenna.

Finally, the surface current distributions for the radial linear and curved parts of the optimum designed dual-arm spiral antenna over the AMC ground plane are shown in Fig.6.15 at the center frequency of 4.5GHz. As expected, the surface current is evenly distributed between the two spiral arms. Furthermore, the current magnitude goes to zero as the waves travel toward the end of each spiral arm.

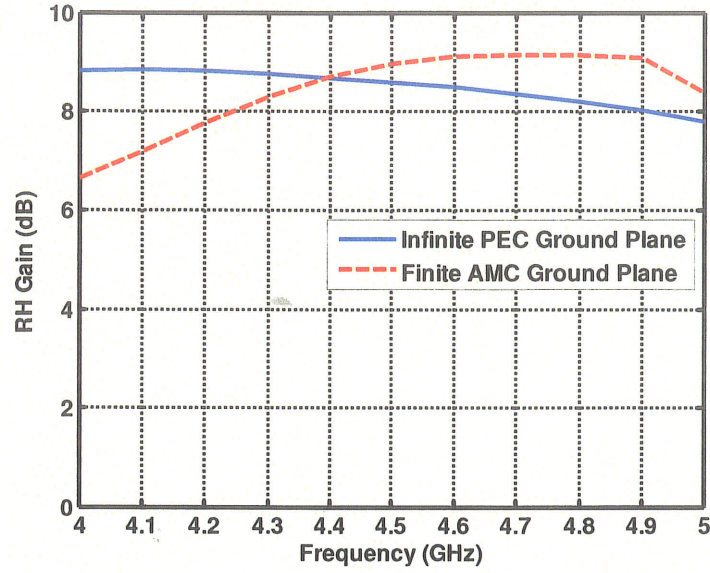


Fig. 6.14: Right-Hand gains of the dual-arm spiral antenna over infinite PEC shown in Fig.6.1 when $\alpha_{st} = 6\pi$, $n=1.42$, $a = 0.455\text{mm/rad}$, $h = 16.67\text{mm} = \lambda_0/4$, and the AMC ground plane shown in Fig. 6.8, when $\alpha_{st}=6\pi$, $n=1.05034$, $a=0.28\text{mm/rad}$ at $\theta=0^\circ$.

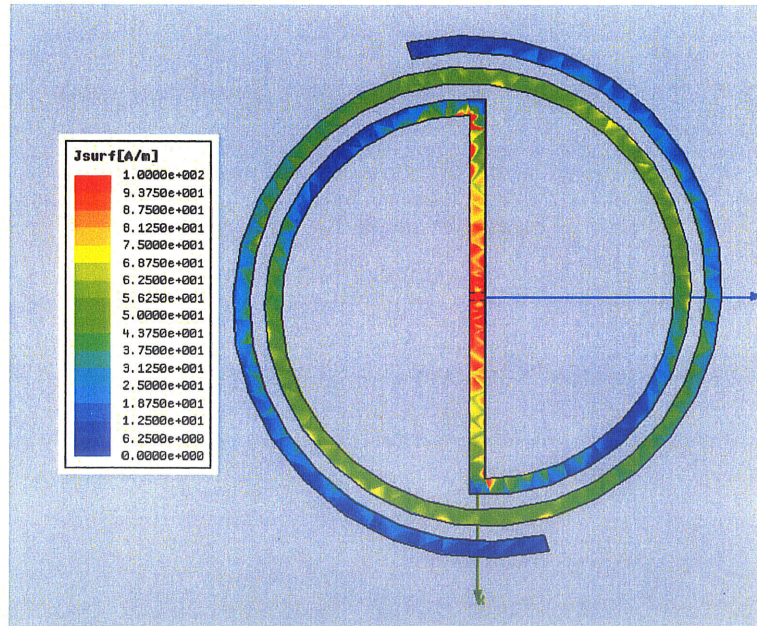


Fig. 6.15: The surface current distribution over radial linear and curved sections of the dual-arm spiral antenna over the AMC ground plane shown in Fig. 6.8, when $\alpha_{st}=6\pi$, $n=1.05034$, $a=0.28\text{mm/rad}$, at $f=4.5\text{GHz}$.

6.4 Summary

Dual-arm Archimedean spiral antennas over both infinite PEC and finite AMC ground planes were studied over the center operating frequency of 4-5GHz. The planar size of the AMC ground plane was $0.836\lambda_0 \times 0.836\lambda_0$, similar to the one used in chapter four. A curl antenna was excited by a probe feed, whereas a dual-arm spiral antenna needed a balanced feed with an appropriate phase difference of 180 degrees. A dual-arm spiral, due to its symmetrical geometry, generates more symmetric radiation and axial ratio patterns than its single-arm counterpart. In order to keep the good CP performance at the same frequency, dual-arm spiral parameters needed to be optimized due to the resonant structure of the AMC ground plane and different feeding network. The optimization process started with the optimum values found in chapter three for the single arm spiral curl antenna and the PEC case, and chapter four for the AMC case. It was shown that, the antenna size shrank compared to the single-arm case. A perfectly symmetric CP performance was observed over both PEC and AMC ground planes. Meanwhile, a low-profile dual-arm spiral antenna was obtained with the height of $0.02\lambda_0$ from the AMC ground plane, providing an excellent circular polarization and wide beamwidth at the broadside direction. This type of antenna is highly useful in wireless communication systems.

Chapter 7

Conclusion

7.1 Summary

This thesis provided a parametric study of both single arm spiral curl and dual-arm Archimedean spiral antennas over infinite PEC and finite AMC ground planes, at the center operating frequency of 4.5GHz. These antennas produced right-hand circularly polarized waves with wide beamwidths. When each of the above antennas was backed by a traditional PEC ground plane a minimum height of a quarter-wavelength was required for satisfactory performance. However, the use of an AMC surface as a ground plane made a noticeable reduction in the height to a small fraction of one wavelength, resulting in a low-profile antenna structure. The AMC ground plane composed of a planar array of square patches, backed by a grounded dielectric slab without vias. All numerical studies were carried out using the Finite Element method.

The investigation of a curl antenna over an infinite PEC ground plane demonstrated that the optimum circular polarization was obtained with the expected distance of a quarter-wavelength, between the curl antenna and the PEC ground plane. Therefore, the resulting antenna was too bulky. This distance was reduced to $0.02\lambda_0$, by using a 4×4 array of square patches as the AMC ground plane, with a finite planar size of only $0.836\lambda_0 \times 0.836\lambda_0$. The RHCP copolar gain of this low-profile antenna was 8dBic, similar to the traditional PEC ground plane. The antenna was further studied to understand the effect of its linear feed section. Unlike the curl antenna over the PEC ground plane, this linear part was found to have a profound effect on the center operating

frequency of the curl over an AMC ground plane. However, this problem was solved by extending the spiral toward its center. Also, a curl antenna over another AMC ground plane with a 2×2 array of square patches was examined. This small number of patches resulted in a poor CP performance.

To verify the simulation results, the optimized low-profile curl antenna over the AMC ground plane of 4×4 array of square patches was fabricated and tested. The measurement results were in a good agreement with the simulation ones, when a small air-gap was placed between the two substrates.

To complete the study, a low-profile dual-arm Archimedean spiral antenna was also investigated at the distance of $0.02\lambda_0$ over the AMC ground plane, consisting a 4×4 array of square patches. Perfectly symmetric CP radiation patterns were obtained by retuning the optimized values found from the low-profile curl antenna. Furthermore, the antenna size shrank comparing to the single-arm curl antenna.

As a result, two different spiral antennas were developed using a finite AMC ground plane. The in-phase property of the AMC's allowed placing the spiral antennas at a much closer distance of $0.02\lambda_0$ from the AMC surface, thus resulting in a low-profile structure. These low-profile antennas exhibited excellent circular polarizations around the boresight direction.

7.2 Future work

The following research topics need to be studied relating to the low-profile Archimedean spiral antenna over an AMC ground plane.

- Study on the input impedance of the single- and dual-arm spiral antennas over an AMC ground plane.
- Improve the frequency bandwidth of the presented low-profile antennas.
- Design a practical feed networks for dual-arm spiral antenna in order to measure the antenna performance practically and verify the simulation results.
- Use each optimum curl and dual-arm spiral antennas as radiating elements in array configurations for high gain applications.
- Investigate different geometrical shapes of patches used in the AMC ground plane such as circular, rectangular, ring and so on.
- Employ different dielectric materials between the antenna and the artificial ground plane.

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