Printed wire antennas for wireless communications

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Printed Wire Antennas for Wireless Communications

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School of Electrical & Electronic Engineering

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in fulfillment of the requirement for the degree of
Master of Engineering

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STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other university or institutions.

08/07/2005
Date

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SUMMARY

The printed wire antennas have wide applications in wireless communications in recent years. They have kept the attractive features of the conventional wire antennas such as wideband, simple feeding and efficient radiation, while having additional advantages of stability, accurate fabrication at high frequency and ease of designing matching circuits. In this thesis several printed wire antennas with different type of feedings have been designed, implemented and measured. They all have desirable characteristics such as compact size, wideband circularly polarization, and impedance matching. Both the calculated results and measured results are presented and they agree with each other quit well.

Chapter 1 Introduction

1.1 Motivation

An antenna is a transition device, or transducer, between a guided wave in a cable or waveguide and a free-space wave in free space [1]. In other words, the antenna is a means for radiating or receiving radio waves [2]. For successful wireless communication system, a well-designed antenna is a very important component. The electromagnetic energy from a transmitting source would be localized without an efficient antenna, and thus the wireless information transmission over long distance cannot be realized.

Fig. 1.1 Wire antennas

Since the first radio antenna was built by Heinrich Hertz in 1886, Guglielmo Marconi and his followings had improved various functions of the antennas and extended them for wide applications in wireless communication. The successful development of the antennas facilities our lives and contributes a lot to the

modern civilization. The antennas have bewildering varieties for different applications in navigation, aerospace and so on. Among the huge antenna family, wire antennas are the oldest, simplest, and most versatile type. They are built by linear or curved metallic wires and include different types of monopoles, dipoles, and loop antennas etc. Figure 1.1 shows some basic types of wire antennas. Wire antennas possess many desirable characteristics such as wide band, simple feeding, efficient radiation, and ease of fabrication. Moreover, these antennas have found wide applications in many practical situations such as television and radio broadcasting, mobile phone, global positioning system and so on.

However, wire antenna is not very suitable for the high frequency applications. This is because with the increasing of frequency, the overall size of the wire antenna becomes smaller and smaller. Hence it is difficult to manufacture the antenna precisely using the traditional mechanical process, and realize the radiation characteristics that are theoretical predicted. The appearance of the printed antenna gives a solution on this problem. The printed antenna can achieve high accuracy in fabrication even at very high frequencies using the matured etching and photolithography technique. Thus the whole manufacture process is simple, accurate and low-cost. Moreover, the printed wire antenna is much more stable than the wire antenna because the planar dielectric layer can provide a supporting layer for the antenna structure. It also has low profile and

is conformable to either planar or non-planar surfaces. Its highly stability and compatibility make it especially suitable for integration with the microwave and millimeter-wave integrated circuit (MMIC). Furthermore, the ground plane of the antenna can serve as a reflector to achieve a unidirectional radiation pattern.

Due to the inherent advantages of the printed wire antenna listed above, printed wire antenna has been studied extensively and developed briskly and widely. Numerous approaches in different shapes, including monopoles, dipoles, loop antennas and curved antennas, etc., have been investigated. All of them exhibit one or more desirable characteristics such as low profile, wideband and high radiation efficiency. In order to fulfill the requirements of antennas for different applications, various techniques have been proposed to improve antenna impedance and radiation characteristics. For examples, a folded dipole was developed with a more compact size and attractive impedance characteristics in [3], and a sleeve dipole was used to realize mechanical strength, high gain and extended bandwidth in [4].

In order to investigate the characteristics of the complex geometry antennas and to simplify the design procedure, various analysis methods have been proposed. In the 1960s, R.F. Harrington unified the majority of the numerical methods by identifying the Method of Moments (MOM) as the underlying principle for them. Computations employing the generalized MOM invariably reduce the

complicated physical problems that are enforced by the Maxwell's equations and the boundary conditions, into a set of integral equations and then a finite order matrix equation by properly defining the basis and testing functions with the same number [5]. These simultaneous linear matrix equations can be solved numerically by forming the iterative computer code. MOM has been commonly considered as one of the most powerful analysis techniques in modeling and design of wire and printed antennas. With the help of analytical Green's function, the numerical discretization is only implemented on the wire and printed strip surface, thus creating a very low order of final matrix equations as compared with other numerical techniques.

On the other hand, the printed wire antenna is different with the conventional wire antennas. It is normally printed on the surface or interface of a dielectric substrate. In this way, the ground plane with large dimension can be effectively used as a reflector to get a unidirectional radiation beam. In 1988, H. Nakano and etc. presented a real-axis numerical integration method to investigate printed wire antennas with arbitrary wire configurations [6]. Since the Pocklington-type and the Halién-type integral equations normally used in MOM are difficult to handle the printed wire antennas, a numerical method using Sommerfeld type integral equation was reported to do the analysis of square loops, meander dipoles and spiral antennas in 1989 [7]. In addition to the MOM, the other methods used to investigate antennas include finite element

method (FEM) and finite difference method (FDM). In the previously mentioned MOM, the substrate and the ground plane were usually assumed to be infinite to simplify the analysis, while in reality it is not the exact case. In order to deal with the more practical case, a finite-difference time-domain (FDTD) method was proposed in 2002 to numerically analyze an antenna printed on a finite size dielectric substrate [8]. As various numerical techniques are developed, many electromagnetic simulation and optimization packages, such as IE3D and ADS, have been recently commercialized. They provide the RF engineers and scholars with powerful tools in the analysis and design of complicated RF and microwave antennas with accuracy results. They also help one to reduced the production-development-circle period and decrease the potential cost. By applying these numerically methods or codes, the current density along the antenna can be well obtained and thus derive the other parameters of the concerned antenna, such as radiation pattern, directivity, input impedance, and polarization.

Polarization of an antenna is the property of the electromagnetic wave transmitted or radiated by the antenna, which describes the time varying direction and relative magnitude of the electric-field vector. It can be classified as linear, elliptical and circular polarizations, where the linear and circular polarizations are the two special cases of the generalized elliptical polarization. In the wide applications of satellites and long distance wireless communications,

the low profile and circularly polarized antennas have been receiving much attention recently. They have an inherent property that is insensitivity to the ionospheric polarization rotation. Thus this kind of antennas always can achieve reasonable transmitting and receiving efficiency. Circular polarization can be realized by exciting the two orthogonal modes with 90° phase difference and equal magnitudes [9]. This can be accomplished by various methods and an enormous numbers of circularly polarized antennas have been proposed. One example is to realize circular polarization by designing the feeding network of arrays of linearly polarised antennas with single or more feedings [10]. However, this technique increases the complexity of the design and fabrication. Some resonant antennas, such as microstrip antennas, can radiate the circular polarized wave by adding the perturbation elements such as a slit or stub in the diagonal line of a squared patch [11]. Moreover, some non-resonant antennas, including spiral antennas [7], [12], axial mode helical antennas [13], and loop antennas [14], [15] can also radiate circular-polarized wave with extended frequency bandwidth. This project will mainly focus itself on the development of a new class of non-resonant printed wire antennas with circular polarization. They have been exhibited many attractive features such as low profile, relative simple configuration, and versatility etc. Figure 1.2 gives some examples of this antenna type.

Fig. 1.2 Printed wire antennas with circular polarization

As mentioned above, the current distribution along the wire antenna determines the properties of the electromagnetic wave radiated from this antenna. When a curl antenna has a current distribution with a constant amplitude and linearly changing phase of a travelling wave, it can radiate a circularly polarised wave [16], [17]. With this principle, various printed wire antennas with circular polarization have been developed so far, and some novel ones will be exploited in this thesis.

The matured MMIC technologies have found wide applications in the fields of wireless, telecommunication, radar and satellite communication systems nowadays. The inherent features of the printed wire antennas make them be easily integrated with various planar integrated feeding lines, including

microstrip lines, slotlines, coplanar waveguides and coplanar strips as shown in Figure 1.3.

Fig. 1.3 Planar transmission lines

Impedance matching can be achieved by adjusting the dimensions or patterning the configurations of these planar feeding lines relying on the commercial software. Due to their geometrical characteristics, the printed wire antennas may have coplanar stripline (CPS) or microstrip feeding networks [18], [19], while the slot antennas may use coplanar waveguide (CPW) or slotline feeding networks [20], [21]. To feed a number of antenna elements in series or shunt way, the transition between the different types of planar feeding lines is sometime requested and it may be realized by Tee-junctions [22]. Furthermore, in the exploitation of various passive and active antenna arrays, extensive investigation has been well carried out on the antenna feeding blocks using the above listed planar integrated transmission line technology.

1.2 Objectives

The main objectives of this project for the Master of Engineering program are described as below:

1. To enhance the knowledge of electromagnetic and microwave engineering theory such as transmission lines and impedance matching network, collect practical experience in the theoretical analysis and hands-on implementation.
2. To better understand the antenna theory, particularly in the aspects of antenna basic parameters, working principle, feedings, applications and so on; earn a comprehensive understanding of printed wire antennas, especially those of radiating the circularly polarized wave, propose and develop several antennas with desirable characteristics and improvements as case study.
3. To get an experience of a whole research and development circle, including literature review, theoretical design and optimization, and practical fabrication and measurement.
4. To have an overview of the various antenna analysis methods, such as MOM and FDTD, and get familiar with the electromagnetic simulation tools, including IE3D and ADS, in the design of wire and printed antennas.
5. To learn the fabrication process and the experimental techniques using different equipments, in particular, to measure the return loss by the

network analyzer, radiation pattern and axial ratio by the anechoic chamber, and improve the capability in collecting and analyzing data, finding the possible reasons, and developing new approaches to improve the performances.

6. To study the way in writing scientific papers and documents, and to improve communication skills with supervisors, technicians and other students.

1.3 Major contributions to the thesis

In this project, two major contributions have been made.

Firstly, a broadband circular-polarized printed hemispherical helix antenna has been proposed and studied theoretically and experimentally. It exhibits many attractive advantages such as low profile, self-matching, and good axial ratio performances.

Then two printed dual-loop wire antennas with different feedings, i.e., CPS and microstrip line, have been presented and investigated. These two antennas significantly reduce the size ~30% and have relatively desirable axial ratio and impedance bandwidth.

Moreover, 3 articles have been prepared to report the contributions of this thesis.

One of them, named “Printed hemispherical helical antenna for GPS receivers”, has been published in the *IEEE Microwave and Wireless Components Letters*. The other two are still under review for the possible publications.

1.4 Organization of the thesis

The rest parts of this thesis are organized as follows:

Chapter 2 introduces a novel printed hemispherical helix antenna for GPS receivers. The requirements and design guidelines of a GPS antenna are presented first. The geometry of the antenna is then presented and the major functions of different parts of the antenna are comprehensively studied. The full-wave design and analysis tool, IE3D, was used to optimize and analyze the antenna by executing the numerical simulation and illustrate theoretically basic antenna characteristics, such as current distribution, radiation pattern, return loss etc. The optimized antenna was then fabricated and tested. Finally the measured data is compared with the simulation results to verify the attractive performances of the designed antenna.

Chapter 3 describes a printed dual-loop spiral antenna with broadband circular polarization. The whole structure of this antenna consists of a radiation part and a feeding block. The effects of the several physical parameters of this antenna on radiation performance have been extensively investigated. Later on, the

influence of the feeding block has been studied and the current distribution along the antenna is shown to look insight into the principle of this proposed antenna. An antenna sample was fabricated to verify the predicted performance. Both of the calculated and measured results are presented and compared. The possible reasons on the similarity and difference between them are also discussed.

Chapter 4 presents a modified antenna based on its initial designed counterpart in Chapter 3. This antenna is printed on single side of a dielectric substrate and fed by the coplanar stripline feeding network. IE3D was again used to undertake the simulation and optimization of this antenna. The simulation results are well confirmed in comparison to with the measured data of the fabricated antenna sample. The differences between them are also discussed.

Chapter 5 draws the conclusion and gives some recommendations for the future work in the aspects of improving the performance of this antenna and establishing a high-gain antenna array with circular polarization.

Chapter 2 Printed Hemispherical Helical Antenna for GPS Receiver

After earning a comprehensive understanding of the working principles, analysis method and basic characteristics of printed wire antennas, especially those with circular polarization, a printed hemispherical helical antenna was designed, fabricated and measured as a case study. This antenna has many attractive properties such as low profile, easy of fabrication and integration, and low return loss with reasonable desired 3-dB axial ratio bandwidth. Hence, it has a possible application for various wireless communication systems including GPS receivers.

2.1 Global positioning systems

The Global Positioning System, or GPS in abbreviation, is a worldwide accessible radio-navigation system. Its carrier frequencies are set to 1.227GHz and 1.575GHz in the L-band. This system is established by 24 satellites and linked with the corresponding ground stations. GPS has been found a wide application in the modern wireless communications, including ships, missiles, cars, construction machines and even personal computers. The principal idea of the GPS stems from the triangulation theorem. The satellites are used as reference points to determine the locations on earth. By accurately measuring the distance from a point on earth to 3 satellites, the position at anywhere on

earth can be decided. A GPS receiver makes use of the travelling time of radio signals to measure the distance.

Since the radio wave propagation is used as the means of information transmission, the performance of the antenna is vital to the performance of the whole system. The specifications for a high-precision GPS antenna include hemispherical coverage and superior rejection to the multipath signals. Rotation of the electromagnetic wave polarization occurs for long distance or satellite communications due to the existence of the ionosphere. Multipath arises when the GPS transmitted signal takes different paths to the receiving antenna. In this way, the signals from these paths are added together with different phases. This results a significant amplitude and phase distortion [23]. The major part of multipath signals occurs near the ground because of large amount of obstacles such as buildings and vehicles. Good multipath rejection can be accomplished by using circularly polarized antenna with sharp drop-off at low elevation angles [34]. To achieve the optimum signal transmission and reception, the transmitting antenna and the receiving antenna should have the same rotation direction of circular polarization, which is basically right-hand for GPS antenna. Various GPS antennas have been developed for airborne platforms, ground vehicles, and portable systems. However, they usually have one or more defects such as large size, heavy weight, high cost and complex feeding networks.

2.2 Spherical helical antenna and hemispherical helical antenna

Helical antenna has two main modes of operation, normal mode and axial mode.

When the helical antenna works in normal mode, the radiation pattern is broadside [25]. When it works in axial mode, the radiation pattern is endfire [13]. As mentioned in Chapter 1, the non-resonant axial-mode helical antenna with a travelling current distribution can radiate circularly polarized wave over a broad range of frequency with fairly high gain. These properties make it particularly desired for transmitting and receiving signals of radio frequency. Hence, a well-designed axial-mode helical antenna can fulfil the requirements of the hemispherical coverage and good multipath rejection stated above for a high precise GPS receiver.

Fig.2.1 Spherical and hemispherical antennas

The cylindrical helical antenna has been investigated comprehensively since it was proposed, and a lot of modifications have been done on its geometry to improve the antenna performance [26]. Some examples are quadriplanar helical

antenna [27], square helical antenna [28], spherical antenna [29]-[31] and hemispherical helical antenna [32], [33]. In this project, the printed hemispherical helical antenna is proposed based on the comprehensive studies of the later two antennas. The geometries of these two antennas are described in Figure 2.1. As shown in Figure 2.1.a, the spherical helical antenna is constructed by winding the inner conductor of a coaxial cable on a spherical surface, and the outer conductor is connected to the ground plane. There is a constant spacing between two adjacent turns, so the antenna structure can be uniquely described with only two parameters, the radius of the sphere and the number of turn. The spherical helix can be easily constructed and mathematical expressions that describe its geometry can be easily formulated. The original point of the spherical coordinates system coincides with the lowest point of the sphere, and the coordinates values of the wire, which form the antenna, can be calculated by the following equation:

$$r = a, \theta = \cos^{-1}\left[\frac{\phi}{2N\pi} - 1\right], (0 \leq \phi \leq 2N\pi) \quad (2.1)$$

where a is the radius of the sphere, N is the number of turns of the helix, and r, θ, ϕ are the spherical coordinates. Hence the projection of spacing between two adjacent turns on the z -axis is $2a/N$.

The spherical helical antenna inherits the advantages of the conventional cylindrical helix. It has a fairly high gain and excellent circular polarisation over a wide frequency range. Moreover, it has a marked improvement of

circular polarization over a major portion of the main beam in a narrow frequency range. Its radiation pattern is a broad main lobe with almost no sidelobe and a low level backlobe. For a 10 turns spherical helical antenna, a gain about 9.5dB in the axial direction can be obtained. These properties and its compact size make it suitable for mobile radio communication systems with low channel capacity.

The hemispherical helical antenna is an extension of the spherical helical antenna. Compare with the original spherical helical antenna, it has many advanced features, including smaller size, more robust and low-profile structure. The geometry of the hemispherical helical wire antenna is shown in Figure 2.1 (b). Similar to the structure of spherical helical antenna, the metallic wire winds upon a hemispherical surface with a constant spacing between the two successive turns, and it is located above the ground plane at a height of h . Since the antenna size is fixed irrespective to the number of turns of the helix, the power gain and the radiation pattern are not sensitive to the different number of turns. On the other hand, the current distribution along the wire and the axial ratio can be easily changed by the number of turns of the helix. From the investigations done in [32], it is found that the 3dB axial ratio bandwidth increases with the number of turns, while the axial ratio decreases with it. A 5-turn hemispherical helical antenna has a wide 3dB bandwidth almost two times of a 3-turn one. The bandwidth is $\sim 14.6\%$ with a high gain more than 9dB,

and the axial ratio elevated angle range of 3dB is found about 90° at the centre frequency.

2.3 Geometry of the printed hemispherical helical antenna

Fig.2.2 Geometry of hemispherical helical antenna

The printed hemispherical antenna is a modified version of the wired hemispherical antenna. It can achieve almost the same characteristics as the original wired hemispherical antennas and is further self-matched with just a small modification to the original design. Furthermore, by making the antenna into a printed form, a more stable and durable structure can be resulted. This solves the loose-structure problem of the wired antennas and makes it easier in manufacturing.

Figure 2.2 (a) and (b) gives the top view and side view of the proposed antenna. As shown in this figure, a five-turn hemispherical helix is printed on a hemispherical surface and is fed by a coaxial cable at point O' through a S-shape matching-section design with three straight strips. The constant spacing between the adjacent two turn of a N -turn antenna is equal to a/N .

There are two operation modes of helical antenna, normal mode and endfire mode. In end fire mode, the antenna can produce circularly polarized radiation over a wide frequency range and it is more efficient. This mode can be achieved by adjusting the antenna diameter to a proper value. In more detail, the normalized frequency range must satisfy the following inequality:

$$3/4 \leq C/\lambda \leq 4/3 \quad (2.2)$$

where C is the circumference of the antenna and λ is the free-space wavelength.

The radius of the polystyrene hemisphere used as the hemispherical surface in the sample antenna is 18.78mm, and the thickness of the copper strip of the antenna can be ignored. Hence the radius of the antenna is approximately equal to the one of hemispherical polystyrene, and the antenna perimeter is 118mm. According to the similarity between cylindrical helix and hemispherical helix, this inequality should be applicable to hemispherical helical antenna with some modifications. With the help of the simulation tool IE3D, the optimum value of the ratio between the circumference of the antenna and the free-space wavelength is found to be $C/\lambda=1.18$ at 3.01GHz with corresponding free-space wavelength of $\lambda_0=99.67\text{mm}$. Therefore the antenna radius $a=18.78\text{mm}=0.194\lambda_0$ and the copper strip used to build the antenna has a width $w=2\text{mm}=0.02\lambda_0$. It should be noted that the desired center frequency could be easily scaled to other frequencies as required.

Since the geometry of the hemispherical helical antenna is just upper half of the spherical helical antenna. Its structure formula can be derived from Equation (2.1) to calculate the coordinates of the centerline of the copper strip:

$$r = a, \theta = \cos^{-1}[\pm(\frac{\phi}{2N\pi} - 1)], 2\pi N \leq \phi \leq 4\pi N \quad (2.3)$$

where a is the radius of the hemispherical antenna, N is the number of turns of the helix and r, θ, ϕ are the spherical coordinates. The “+” or “-” sign indicates that the helix is right-handed or left-handed. As stated in the previous part, the 5-turn hemispherical helical antenna has the lowest axial ratio, so the number of

turns of the antenna samples is chosen 5. Thus, the range of ϕ is 10π - 20π , which corresponds to the upper half sphere. The range is scaled down to the commonly used range for simplicity, $0^\circ \leq \phi \leq 360^\circ$. As a right-handed polarization is desired, the “+” sign is used to calculate the values of the coordinates to build the antenna sample.

The total length of the copper strip should be known to construct the antenna. For the twisted structure of the hemispherical helix, an integral equation is derived as following:

$$L = \int a \sqrt{1 + (N\pi)^2 \sin^4 \theta} d\theta \quad (2.4)$$

The total length can be then calculated numerically. By substituting the values $a=18.78\text{mm}$ and $N=5$ into the equation, the value of the total length is found to be 467.5mm. According to the simulation results, the length of the hemispherical part doesn't affect the operation frequency and the power gain so much. However, it plays an important role in the circular polarization performance. The axial ratio decreases significantly even if the top of the hemispherical helix is cut a bit.

The matching to the input impedance of an antenna is also an important consideration in antenna design. In order to obtain a low return loss and VSWR of the antenna fed by the 50Ω transmission line, the input impedance of the antenna should be adjusted to the value around 50Ω . Usually a tapered feeding

section is connected to the feeding point, at the cost of the complexity and the cost of the design. Hence, a bending section is formed by 3 straight strips as the self-matching block for the solution of this problem as shown in Figure 2.3.

Fig. 2.3 Matching strip section

As shown in [32], the length of the hemispherical helix takes a critical role in controlling the axial ratio of the antenna and the impedance of the antenna at the center frequency comes with a large negative imaginary part of capacitive reactance. By properly adjusting the lengths of the three strips in Figure 2.3, L_1 , L_2 and L_3 , the antenna can be matched in impedance at the desired frequency where the axial ratio is the lowest. It can be explained that the matching section introduces an inductive reactance to neutralize the capacitive reactance of the hemispherical antenna part. With the help of the simulation tool IE3D, it is found that the frequency with the lowest axial ratio changes inversely with the change of the total length of this part, and the optimum lengths of the three strip

sections are chosen as, $L_1=6\text{mm}=0.06\lambda_0$, $L_2=10\text{mm}=0.1\lambda_0$ and $L_3=5.5\text{mm}=0.055\lambda_0$, respectively. The total length of the antenna, including the hemispherical helix and the matching section, is $L_{total}=490=4.92\lambda_0$, which is about integers, i.e., five of the free-space wavelength.

2.4 Simulation, fabrication and measurement

The simulation and optimization of the antenna were done with the help of full-wave design and analysis tool, IE3D. The antenna was drawn according to the coordinates of the centerline calculated by the Equation (2.3) with the desired width. In order to simplify the calculation and save computational time, the metallic strip used to build up the antenna was assumed with perfect conductivity and the ground plane used in the simulation was considered as infinite extent with perfect conductivity. Since IE3D cannot simulate a twisted smooth 3D geometry, the antenna's layout was formed by a series of polygons as shown in Figure 2.2. The simulation results achieved so far can be considered quite accurate. Of course, the small discrepancy can be further minimized by selecting the large number of polygons and the non-uniform meshes in the IE3D software at the cost of large CPU memory and long CPU time. The whole antenna is simulated above the infinite ground plane and fed through a vertical port with a 50Ω impedance. The primary antenna characteristics, such as return loss, axial ratio, radiation pattern, are simulated and the results are presented in details in the next section.

An antenna sample was fabricated to validate the calculated results. In practical implementation, the antenna dimensions used were presented in section 2.3. A polystyrene hemisphere serves as the hemispherical surface and a copper tape with a negligible thickness is used to construct the antenna and the matching sections. The copper tape was stuck firmly onto the polystyrene hemispherical surface. Since the infinite ground plane is not realizable practically, a square copper plate of $248 \times 248 \text{ mm}^2$ ($\lambda_0/4$) was used as the ground plane, and a SMA connector was attached to the center of the ground plane to feed the antenna.

For the measurements of the antenna characteristics, the network analyzer and the microwave anechoic chamber were utilized. The HP8753E network analyzer was used to measure the return loss, input impedance or VSWR. A 50Ω 1m long coaxial cable was used to connect the feeding point of the antenna to the channel 1 of the network analyzer. Before the measurement, the full-port calibration procedure was done to ensure the accuracy of the experimental results using the standards of open, short and 50Ω loads. The state or data of the analyzer after calibration can be saved for reloading to save the time of future measurements. Then the antenna was connected to the analyzer for the frequency response measurements. The results can be illustrated in either Logarithm or Smith chart format. The testing data was converted to ASCII file and saved for later processing by ADS or other software. The radiation patterns of the antenna were measured in the microwave anechoic chamber. This

anechoic chamber is an enclosed space designed with walls that can effectively absorb incident electromagnetic waves, thus creating a free-space environment for testing. The antenna under test was fixed on a plastic support and it can be rotated horizontally in an automatic way. A simple waveguide horn antenna that can radiate linearly polarized electromagnetic wave at proper frequency range was selected as the standard antenna. The centers of this horn and the antenna under test were aligned to the same height level for precise results. And the distance between them should be larger than $2D^2/\lambda$ for far-field testing, where D is the largest dimension of the waveguide and the antenna. The distance in this test was 1.5m and it is well satisfied with the above criteria. Because the measurement was done in an enclosed room, the horizontal rotation of the antenna was controlled through the use of software called AL2000. To measure the radiation patterns, the testing angle should be increased step by step to prevent wire broken or motor stuck. Because the antenna under test was fixed, the waveguide was firstly put horizontally to measure the radiation pattern of elevation electric field, E_θ , and then changed vertically to measure the radiation pattern of azimuth electric field, E_ϕ . The measured data files were saved for further processing, analysis and discussion.

2.5 Results and discussion

The calculated and measured results of return loss and radiation pattern are presented and compared in this section. Comprehensive investigations on the

differences and similarities are carried out, discussions are done and possible reasons are then suggested. The simulation frequency range for the return loss was $1 \leq C/\lambda \leq 1.4$. Normalized frequency value was used for the easy scaling of the antenna size for the desired center frequency. Because the simulation of axial ratio is relatively time consuming and only the frequency range around central centre frequency is considered, the simulation frequency range chosen for the calculation of axial ratio is $1.10 \leq C/\lambda \leq 1.26$.

2.5.1 Current distribution

The simulation tool IE3D has the advanced function to provide the current distribution along the strips of the antenna. It uses small triangle cells to show the current distribution. The direction of the triangle alignment indicates the direction of the current flow and the color shows the strength of the current density. This gives us the direct impression on the current distribution of the antenna.

The current distribution along the hemispherical helical antenna at the center frequency, $C/\lambda=1.18$, is illustrated in Figure 2.4. Light color corresponds to the smallest current of about -40dB and dark color shows the largest current of 0dB . Since the main radiator of the antenna is the hemispherical helix, only the top view of the antenna is provided here. The current distribution largely determines the performance of an antenna. A reflected current from the open

end of an antenna will produce circular polarization radiation in the opposite sense of the desired one, hence damaging the purity of the wanted circular polarization. As shown in the figure above, the current at the open end of the antenna is the lowest, which means just very small with almost no reflected current existing at this point. Hence the circularly polarized wave produced by the reflected current becomes negligibly small so as to avoid the distortion of circular polarization with requested left- or right-handed characteristic. Therefore, a circular polarization with high purity can be well obtained at this operating frequency.

Fig. 2.4 Current distribution along the antenna at $C/\lambda=1.18$

2.5.2 Axial ratio

The polarization of an antenna is determined by the phase and magnitude

differences between the two orthogonal far-field components of electric field. For elliptical polarization, the axial ratio is the ratio between the lengths of the major axis and the minor axis of the ellipse traced by the end of electric field vector. For a pure circular polarization, the orthogonal far-field components have the same magnitude and $\pi/2$ phase difference so that the axial ratio is equal to 0dB.

Figure 2.5 shows the axial ratio of the circular polarization as a function of the normalized frequency C/λ , where $\theta=0^\circ$ and $\phi=0^\circ$. Two cases of the widths of the copper strip have been studied here, with $w=1.5\text{mm}$ and $w=2.0\text{mm}$, to investigate the influence of the strip width on the axial ratio. Very low axial ratios of 0.2dB and 0.4dB are observed at the center frequency at $C/\lambda=1.18$ for the strip widths of 1.5mm and 2.0mm respectively. For narrow band antennas, the bandwidth under the axial ratio definition is calculated by the following equation:

$$BW = \frac{(f_{upper} - f_{lower})}{f_{center}} \times 100\% \quad (2.5)$$

Substituting the values of the upper bound and lower bound frequency of the 3dB axial ratio, the 3dB axial ratio bandwidths are found to be 6% for $w=2.0\text{mm}$ and 7% for $w=1.5\text{mm}$. The shapes of the curves for the two cases are quite similar, and the 3dB bandwidth of $w=1.5\text{mm}$ is just a bit larger than that of the $w=2\text{mm}$ one. Because the influence of the strip width on the axial ratio is quite small, the strip width of the sample antenna is selected relatively large as 2mm for the simplification of practical construction. Moreover, the

simulated variation of the axial ratio with elevation angle θ for the case of strip width $w=2.0\text{mm}$ is shown in Figure 2.6. Two orthogonal planes are selected for the investigation at $\phi=0^\circ$ and $\phi=90^\circ$. It can be seen that the elevation angular coverage with axial ratio less than 3dB is around 60° .

Fig. 2.5 Simulated axial ratio with normalized frequency

Fig. 2.6 Simulated axial ratio with elevation angle at $C/\lambda=1.18$

2.5.3 Power gain

Since antennas act as the means of information transmission and reception over distance, a certain level of power gain should be provided to ensure the efficiency of transmitting and receiving the RF information. As illustrated in Figure 2.7, the gain of the hemispherical helical antenna over the normalized frequency range $1.06 \leq C/\lambda \leq 1.26$ with the 3dB axial ratio range is slightly higher than 8dB for both of the two strip width cases. The maximum gains are about 9dB for $w=1.5\text{mm}$ and 8.8dB for $w=2.0\text{mm}$. Hence this antenna can provide a relatively high gain together with a wide axial ratio bandwidth which is not easily achievable by many other single GPS antennas [34].

Fig.2.7 Simulated power gain with normalized frequency

2.5.4 Radiation pattern

An antenna radiation pattern is a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates [9]. The simulated and measured results of the radiation patterns on the two orthogonal planes of $\phi=0^\circ$ and $\phi=90^\circ$ at the central frequency of $C/\lambda=1.18$ are shown in Fig. 2.8. Figure 2.8 (a) and (b) illustrate the power radiation patterns of azimuth electric field E_ϕ in the xz -plane ($\phi=0^\circ$) and yz -plane ($\phi=90^\circ$) respectively. Figure 2.8 (c) and (d) present the radiation patterns of the elevation electric field E_θ in the two planes. These 2D patterns give a good overview of the performance of the antenna. It can be seen that the antenna has a relatively broad mainlobe in the upper half space on the two orthogonal planes. The patterns approaching the horizontal plane also achieve a gradually diminishing characteristic. These properties meet the requirements that GPS antennas should have a wide angular coverage in the upper half space while keeping the reception near the horizontal plane small for mitigating the ground noise effect. For the E_ϕ patterns, the measured backlobes decrease by at least 20dB from the main lobes. However, for the E_θ patterns, the measured backlobes are larger. It is found that for the E_θ pattern shown in Figure 2.8 (b), in the $\phi=90^\circ$ plane, both simulated and measured results show a relatively large dip at about 40° - 50° . This indicates the onset of a sidelobe as frequency increases.

(a)

(b)

(c)

(d)

Fig. 2.8 Simulated and measured radiation pattern at $C/\lambda=1.18$

2.5.5 Return loss

Return loss is an important specification that an antenna designer should take into consideration. The relationship among the three parameters related to impedance frequency responses is satisfied with the following equations:

$$\Gamma = (Z - Z_0) / (Z + Z_0) \quad (2.6)$$

$$RL = 20 \log |\Gamma| \quad (2.7)$$

$$VSWR = (1 + |\Gamma|) / (1 - |\Gamma|) \quad (2.8)$$

where Z is the input impedance of the antenna, Z_0 is the characteristic impedance of the transmission line which usually equals to 50Ω , and Γ is the reflection coefficient.

Fig. 2.9 Calculated and measured return loss with C/λ

Figure 2.9 illustrates the calculated and measured return loss with the normalized frequency C/λ . The curves include two calculated results for 2 different strip widths, $w=1.5\text{mm}$ and $w=2.0\text{mm}$, and one measured result of strip width $w=2\text{mm}$. In this figure, both calculated and measured results show that the antenna is well matched at about $C/\lambda=1.18$ for both cases of strip width. The calculated result of the strip width $w=2\text{mm}$ is less than -30dB while the experimental one is nearly -20dB . The difference between them may be due to the SMA connector used between the antenna and the feeding cable. The lowest values of return loss for both strip widths are observed near $C/\lambda=1.18$, which coincides with the lowest axial ratio point of the antenna. The simulated and measured fractional impedance bandwidths using the -10dB criterion are both about 6%.

Chapter 3 Microstrip-Fed Printed Dual Spiral-Loop Wire Antenna For Broadband Circular Polarization

After the comprehensive investigation of the open-end non-resonant printed hemispherical helical antenna, this chapter proposes design and implementation of a printed dual spiral-loop wire antenna with low profile, compact size and simple geometry. This antenna is studied in this chapter to radiate circularly polarized wave with broadband axial ratio and wide elevated angle.

3.1 Circularly polarized loop antennas

As mentioned in Chapter 1, there are mainly two types of antennas with circular polarization, i.e., resonant and non-resonant antennas. As a matured technique, the resonant antennas such as circular or square patch antennas, have wide applications in practical design due to their low profile, unidirectional radiation, easy integration with other devices, low cost, light weight and so on [35]. Patch antennas can achieve circular polarization radiation in the broadside direction by technologies of various feed arrangements or slight modifications on the elements, so that two perpendicular degenerate modes are suitably differentiated in resonant frequency. However, these resonator-type antennas have some unexpected drawbacks such as narrow bandwidth and low radiation efficiency.

Although a closed loop wire antenna can only radiate linearly polarized wave, circularly polarized radiation can be achieved by installing a reactive element at a proper position along the loop to create a traveling wave current distribution [36]. This reactive element can be a parasitic component or a gap. As an alternative structure, a single loop wire antenna with rhombic configuration above a ground plane as shown in Figure 3.1(a) was originally reported in [37] to realize the circularly polarized radiation by making an air gap at an appropriate position on the loop. Due to its non-resonant characteristics, this antenna has the widened axial ratio bandwidth as demonstrated in analysis and experiment. Later on, a dual loop antenna using the rhombic one as the element was invented in [38] and then studied extensively in [17] for wideband and high-gain circularly polarized wire antennas. In this design, a pair of air gaps were symmetrically located on the two loops with respect to the feed point and their positions are properly adjusted for circular polarization. The sense of the circular polarization can be easily changed by feeding the antenna with a series or a parallel source. This proposed open-loop architecture had been applied in the design of a polarization-agile wire loop antenna by installing a PIN diode at the gap [39] and a printed high-efficiency rectifying antenna array by feeding the dual rhombic loop antenna elements through the coplanar stripline [40]. Recently, a probe-fed dual opened-loop wire antenna with rectangular configuration shown in Figure 3.1 (b) was presented in [41] for simultaneously realizing broadband circular polarization and impedance matching.

Fig. 3.1 Circularly polarized loop antennas

However, the above-reported rhombic or rectangular loop antennas with air gaps usually have electrically long perimeters ranged from $13.2\lambda_0$ to $1.45\lambda_0$, where λ_0 is the free-space wavelength. Plus, like other wire antennas, the mechanically manufacturing has low reliability and repeatability in mass fabrication especially at high frequencies. Moreover, the probe-fed wire antennas always have some difficulties in practical implementation of impedance matching and feeding networks for array design using mechanical process. Thus these antennas need to be further improved in the design of advanced circularly polarized antennas and arrays.

3.2 Geometry of the proposed dual spiral-loop antenna

The printed dual spiral-loop wire antenna proposed in this chapter provides an improved approach to address the above-listed problematic issues. The antenna geometry is illustrated in Figure 3.2. The two spiral loops are etched on the two opposite interfaces of the RT6002 substrate with the following parameters:

dielectric constant $\epsilon_r=2.94$, loss tangent $\tan\delta=0.0012$ and thickness $t=0.762\text{mm}$. They are arranged symmetrically with respect to the central point where $x=y=0$. This printed antenna is then placed above the ground plane at a height of $0.25\lambda_0$, where $\lambda_0=200\text{mm}$ is the free-space wavelength at the frequency of 1.50GHz . The ground plane acts as a reflector to obtain the unidirectional radiation pattern. The two unsymmetrical arms of the opened loops are properly overlapped to make up a small-turn spiral loop so that to miniaturize the overall dimension. In order to produce circularly polarized radiation, the two arm lengths, a and b , are properly differentiated in analog to the unsymmetrical position of an air gap in the circularly polarized dual rectangular loop antenna proposed in [41]. The optimum values of them are found to be $a=0.639\lambda_0$ (138.5mm) and $b=0.56\lambda_0$ (112mm) at 1.50 GHz, respectively. The x -axis side length is set as $w=0.239\lambda_0$ (47.75mm) while the y -axis side length is measured as $l=0.313\lambda_0$ (62.5mm). Using the parameters given above, the overall circumference of each individual loop is significantly reduced from $1.45\lambda_0$ (290mm) of the rectangular opened loop [41] to $1.1\lambda_0$ (220.5mm), or by a fraction of $\sim 24\%$. The printed wire or strip width used to construct the antenna is consistently chosen as $0.01\lambda_0$ (2.0mm) for the simplification of fabrication. The spacing s between the parallel-coupled strips on the overlapped section is $0.06\lambda_0$ (12mm). These dual spiral loops are electrically linked with a short dipole with length $d=0.075\lambda_0$ (15.0mm) and fed by a delta voltage source at the central position ($x=y=0$). From an alternative point of view, this antenna fed in

series can be considered as a double-sided printed dipole antenna with the end-loading of a pair of spiral loops. It is expected that this double-sided antenna can realize the enlarged bandwidth and easy implementation of matching network as studied in [42, 43].

Fig.3.2 Geometry of the proposed antenna

3.3 Numerical results

Similarly to the modeling of the hemispherical helical antenna, the full-wave IE3D software package is again utilized to carry out the design procedure. The antenna is assumed to be put in free space above the ground plane at $\lambda_0/4$ height. The ground plane is assumed to be an infinitely large perfect conductor, whose effect can be considered as an image source. Then an equivalent unit delta voltage source is vertically introduced at the feeding point where $x=y=0$. As such the complex electric current density can be excited along the whole strip

for radiating the power to the free space. In the following section, the magnitude and phase of the current distribution along the spiral loops is demonstrated at the case of the optimized circularly polarized radiation. Then, several critical dimensions are investigated to show their influences on the antenna performance such as axial ratio and input impedance.

3.3.1 Current distribution

(a) Reproduction from reference [41]

(b) Simulated electric current distribution

Fig. 3.3 Simulated electric current distribution at 1.50GHz compares with reference [41]

Figure 3.3 depicts the amplitude and phase of the complex current distribution along one of the dual loops with the optimum dimensions given previously. The lowest axial ratio is equal to 0.2dB at 1.5GHz. Since the two loops are symmetrical, the current distribution on the both of the dual loops should be quite similar with each other. Thus only the current on the left-side or the upper-side is shown here.

The capital letters, A, B, C, D, E, F, and G, under the horizontal axis indicate the corresponding positions on the left-side spiral loop as shown in Figure 3.2. As mentioned above, the unity voltage source is vertically introduced at the feeding point from the upper layer to the lower layer. Figure 3.3 shows that the current amplitude along the whole loop is not changed so much, similarly to that observed in the dual rectangular loop antenna in [41]. The electric current on the segments A-B and E-G has a nearly constant phase, which implies a standing wave distribution along the loop. On the other hand, the current on the segments B-C and C-D has linearly increasing phase. As mentioned above, the traveling wave current distribution leads to the radiation of left-hand elliptically polarized wave. Plus the linearly polarized radiation caused by the short dipole near the feeding point, the superposition of the three distinct radiation polarizations eventually produces the good left hand circularly polarized wave in the z direction as achieved in the simulation and also discussed in [41].

3.3.2 Axial ratio

(a)

(b)

(c)

(d)

Fig. 3.4 Axial ratio versus varied dimensions of the proposed antenna

After the analysis of the current distribution along the strip of the loops of the proposed antenna, the performance of the circular polarization is studied in this section. Several critical antenna dimensions are varied to investigate their influence on the axial ratio of the antenna. As labeled in the geometry layout of the antenna in Figure 3.2, these varied dimensions include the spiral-loop perimeter L , the ratio between the shorter arm length and the longer arm length b/a , the ratio of the width to the length of the loop w/l and the spacing between the two coupled sides of the overlapped section s . In order to clarify the sensitivity of the antenna axial ratio with respect to each dimension stated above, during the simulation, every time only one dimension is changed while others are kept unchanged. Figure 3.4 plots the curves of frequency dispersive axial ratio versus different values of the antenna dimensions in the frequency range from 1.35GHz to 1.65GHz.

Figure 3.4 (a) depicts the axial ratios under three cases of the loop perimeter L , namely, $L=1.23\lambda_0$, $L=1.25\lambda_0$ and $L=1.28\lambda_0$. The change of these three curves is quite regular. The frequency with the minimum axial ratio tends to increase as the loop perimeter L is extended while the minimum axial ratio and its relevant bandwidth are not significantly changed. Figure 3.4 (b) illustrates the axial ratio for three different ratio of the two arm lengths, $b/a=0.75$, $b/a=0.81$ and $b/a=0.84$. The variation tendency is contrary to the one shown in Figure 3.4. (a). The frequency with the minimum axial ratio falls down when the ratio b/a

increases. However, the change of the lowest axial ratio and bandwidth is not sensitive to the length ratio of the shorter arm and the longer arm. Figure 3.4 (c) shows the axial ratio variation with the ratio of the width to the length of the loop for the three values of $w/l=0.74$, $w/l=0.76$ and $w/l=0.78$. Figure 3.4 (d) plots the axial ratio variation with the spacing s between the two coupled sides on the overlapped section for $s=0.05\lambda_0$, $s=0.06\lambda_0$ and $s=0.07\lambda_0$, where $\lambda_0=200\text{mm}$ is the free-space wavelength at central frequency 1.5GHz. These two parameters cause a certain variation in the lowest axial ratio value and the bandwidth, but give little affection on the operation frequency with the minimum axial ratio. From the observations presented above, it is easy to figure out that the former two parameters L and b/a can be effectively utilized to tune the operation frequency per prior specification while the later two ones w/l and s can be adjusted to achieve the better or minimized axial ratio value.

3.3.3 Input impedance

Figure 3.5 illustrates the frequency dispersive complex input impedance at the feeding point where $x=y=0$, versus different loop dimensions as stated in the previous section. The input impedance can be expressed as:

$$Z_{in}=R_{in}+jX_{in} \quad (3.1)$$

where R_{in} is the real part of the impedance or the resistance, and X_{in} is the imaginary part or the reactance.

(a)

(b)

(c)

(d)

Fig. 3.5 Input impedance versus varied dimensions of the proposed antenna

In all the four subplots of Figure 3.5, it is found that R_{in} tends to slowly fall down across 50.0Ω around 1.50GHz while its imaginary counterpart, X_{in} , With negative quantity gradually rises up and approaches zero around 1.60GHz regardless of the varied dimensions. In particular, as shown in Figure 3.5 (a) and (d), R_{in} increases as the loop length L and the overlapped spacing s increases, while X_{in} decreases in an opposite manner. In the meantime, as illustrated in Figure 3.5 (b) and 3.5 (c), The variations in the other two size ratios b/a and w/l only cause the shifting on X_{in} but has negligible influence on R_{in} . Thus X_{in} is more sensitive to the variation of the dimensions than R_{in} .

Based on the above-discussed results, it can be found that the input reactance, X_{in} , basically has a negative non-zero value at the frequency with good axial ratio. This unexpected non-coincidence in axial ratio and the input impedance is also observed in various circular polarized wire antennas [17], [37], [38]. Although in [41], this problem is somehow alleviated, the optimization of several dimensions towards simultaneously achieving the good axial ratio and return loss at the specified operation frequency is quite time-consuming. As the spiral loops are etched on the two opposite surfaces of a substrate, this printed antenna with good axial ratio can be easily matched to the 50Ω feeding line by forming a simple stripline impedance transformer at the feeding point to convert the complex input impedance to a purely resistance with zero reactance.

3.4 Antenna implementation and measured results

In this section, the implementation and measurement of a prototype printed circularly polarized wire antenna with good impedance is presented. All the calculated and measured results are in good agreement, and the antenna shows a broadband circular polarization and impedance matching.

3.4.1 Antenna implementation

In order to prove the validity of the simulation results, a sample antenna was fabricated to do the measurement. As stated in the previous section, the antenna has a negative non-zero input reactance at the feeding point at the central frequency. Thus a simple microstrip line was designed as an impedance transformer for the antenna matching purpose. As shown in Figure 3.6, the dual spiral loops are etched on the upper and lower surfaces of an electrically thin substrate respectively and they are linked with a short stripline section with the length of $0.11\lambda_0$ (22mm) and the strip width of $0.01\lambda_0$ (2mm) on both sides. Next, the lower strip conductor was properly widened to the low-impedance section with the width of $0.04\lambda_0$ (8mm) and the length of $0.055\lambda_0$ (11mm)-long section in order to better install of the SMA connector between the lower and the upper strip conductors in practical implementation. After adding the microstrip matching section and the optimization design of the whole antenna block, dimensions of the two spiral loops were slightly adjusted toward achieving the good axial ratio and return loss simultaneously at the operation

frequency 1.5GHz, where $a=0.695\lambda_0$, $b=0.573\lambda_0$, $d=0.12\lambda_0$, $w=0.234\lambda_0$ and $l=0.333\lambda_0$.

Fig. 3.6 Geometry of the proposed antenna with stripline matching section

The calculated results of axial ratio versus the frequency with and without the stripline section are shown in Figure 3.7. It is found that there is almost no difference between these two curves, thus the influence of the radiation produced by the stripline part can be completely ignored. In more detail, the radiation is basically dominated by the one produced by the electric current flowing on the dual spiral loops and the parasitic effects contributed by that in

the stripline feeding section become negligibly small.

Fig. 3.7 Axial ratio of the proposed antenna with and without the stripline section

After the design of the whole antenna with the stripline matching block, the layout of the antenna was etched on the RT6002 substrate by a milling machine. Then a square metallic plate with the area of $300\times300\text{mm}^2$ was placed in parallel below the printed dual spiral-loop antenna as a reflector for unidirectional radiation. Next a coaxial cable was inserted through the small hole drilled on the center of the metallic plate to link itself with the printed antenna through the SMA connector.

3.4.2 Return loss

The return loss of the sample antenna was measured by the network analyzer. Figure 3.8 shows the calculated and measured return losses of the designed circularly polarized printed strip antenna in the frequency range of 1.35GHz to 1.65GHz. Both the simulated and experimental results are in reasonably good agreement with each other. The fractional bandwidths with the return loss ≤ -10 dB are found about 6.0% and 6.7% in simulation and experiment respectively. In addition, the relevant return losses achieve -20 dB for the calculated result and -15 dB for the measured result at the two slightly different operation frequencies of 1.52 and 1.50 GHz.

Fig. 3.8 Simulated and measured return losses of the designed dual spiral-loop antenna

3.4.3 Axial ratio

Fig. 3.9 Schematic of the implemented printed circularly polarized dual spiral-loop antenna

The microwave anechoic chamber was used to test the axial ratio and radiation pattern of the implemented antenna. Figure 3.9 depicts the 3D schematic of the antenna and the experimental setup for the measurement. A standard horn antenna with linear polarization was used as the receiver. It was placed at a distance about 2.5m from the antenna for the far-field test. The horn antenna was firstly placed horizontally to measure the power of azimuth electric field E_{ϕ} and then placed vertically to test the power of the elevation electric field E_{θ} .

Fig. 3.10 Simulated and measured axial ratio of the designed dual spiral-loop antenna

The axial ratio was then measured as the ratio of the two received powers by rotating the linearly polarized horn antenna 90° with respect to the dash-dot line as shown in Figure 3.9. Figure 3.10 presents the simulated and measured axial ratios as a function of frequency. It can be seen herein that both the two sets of results agree well with each other. Both of the lowest axial ratios are lower than 0.4dB at 1.5GHz and the 3dB axial ratio bandwidths are 13.3% and 15.3% respectively. The slight discrepancy between the calculated and measured results may be caused by the finite extent of an installed ground plane, unexpected small parasitic probe-to stripline transition, non-exact parallel

between the substrate and metallic plate in mechanical mounting and so on.

3.4.4 Radiation pattern

Fig. 3.11 Simulated and measured radiation patterns on the yz-plane

Figure 3.11 (a) and (b) plot the radiation patterns of the two electric fields in

two orthogonal directions, E_θ and E_ϕ , as a function of the elevated angle θ at the frequency of 1.5GHz. Since the antenna is symmetric with respect to the original point where $x=y=0$, only the radiation patterns in the yz -plane are therefore shown here. The calculated radiation patterns are shown in solid lines and the experimental ones are drawn in small circles. Both of the calculated and measured results show the good unidirectional pattern of a broad mainlobe without a sidelobe. The measured results are matched well with the calculated ones in the wide elevated range from -70° to $+70^\circ$, in particular in the broadside direction. Moreover, the magnitudes of the E_θ and E_ϕ are almost same with each other over the plotted θ range, thus achieving a wide elevation range with good circularly polarized radiation.

Chapter 4 CPS-Fed Printed Dual-Loop Wire Antenna with Circular Polarization

In the previous chapter, the printed dual spiral-loop antenna with microstrip feeding has been proposed and studied in depth. The current distribution along the loop and the effects of various critical dimensions on the antenna performance has been comprehensively analyzed and discussed. The proposed antenna has low profile, high stability and easy integration. It can produce broadband circularly polarized radiation over a large elevated angle range. Moreover, impedance matching has been realized with the additional microstrip section at the frequency of good axial ratio. However, this antenna is printed on both sides of the substrate, thus increases the complexity of fabrication. In order to facilitate the issue, this chapter proposes a uniplanar CPS-fed printed dual-loop wire antenna with broadband circular polarization.

Besides the feeding technique using microstrip transmission line, feeding network using coplanar stripline (CPS) has received much attention in the design of uniplanar antennas. Slotlines, CPS and its dual counterpart-coplanar waveguide (CPW) are called coplanar lines where all the conductors are in the same plane, on the top or bottom surface of the dielectric substrate. In particular, CPS has the two separated equal width strips on the same surface of a dielectric substrate [45]. Compare with the microstrip lines, CPS has less dispersion,

lower losses and less dependence on the substrate height. Moreover, passive and active elements can be easily mounted and integrated on the CPS in shunt or series without the need of bonding wires, air bridges or via holes. Plus, the transition from CPS to slotlines is less cumbersome, thereby allowing greater flexibility in the use of mixed transmission media. Due to these advantages of CPS transmission line, many uniplanar antennas fed by CPS have been developed. In [4] a CPS-fed printed dipole was proposed and its input impedance can be easily changed by the offset distance. A bow-tie antenna reported in [46] fed by CPS has an application for UWB communication frequency. In [47] a CPS-fed tapered slot antenna is presented and designed.

The new antenna with CPS feeding has still kept many attractive features of the microstrip-fed antenna such as wide 3-dB axial ratio bandwidth and simultaneously matched by the CPS matching block. Moreover, the total antenna dimension is further reduced to $\sim 13\%$ compared with the antenna reported in Chapter 3. This antenna was also designed and optimized with the help of full-wave simulation tool IE3D. Then a sample antenna was implemented with the optimum dimensions to validate the simulated results. Both of the calculated and measured results are shown in the following sections, including return loss, axial ratio, and radiation patterns. These results are found in good agreement with each other.

4.1 Antenna Design and Geometry Layout

Fig. 4.1 Antenna geometry

The proposed printed dual-loop wire antenna geometry with CPS feeding is shown in Figure 4.1. The antenna is etched on the top interface of the RT 6002 substrate with dielectric constant $\epsilon_r=2.94$, loss tangent $\tan\delta=0.0012$, substrate thickness $t=0.762\text{mm}$, and the metallic strip has a negligible thickness. In order to get a unidirectional radiation pattern, the antenna is placed above a ground plane at a height of $0.25\lambda_0$ [44]. As shown in Figure 4.1, the two identical spiral loops are arranged symmetrically with respect to the central point ($x=y=0$). The two arm lengths, a and b , of each spiral loop are unequally selected and they are determined under the optimum circularly polarized radiation situation as $a=0.573\lambda_0$ (115mm) and $b=0.690\lambda_0$ (138mm) at the center frequency of 1.5GHz,

respectively, where $\lambda_0=200\text{mm}$ is the free-space wavelength. The y -axis side length is measured as $0.303\lambda_0$ (61mm), the x -axis side of the loop is equal to $0.231\lambda_0$ (46.25mm), and the spacing between the overlapped strip sections is $s=0.05\lambda_0$ (10mm). Thus the loop circumference is about $0.96\lambda_0$ (192mm). Compare with the one presented in Chapter 3, which equals $1.1\lambda_0$ (220.5mm), the loop circumference is reduced about 13%. The short horizontal dipole in the center which connects the two loops has a length of $w=0.105\lambda_0$ (21.0mm). Therefore, the whole structure of the antenna can be considered as an end-loaded dipole with series feeding. The strip width of the antenna is selected as a constant value of $0.01\lambda_0$ (2.0mm) for the ease of implementation.

Fig. 4.2 Input impedance without the CPS matching block

Although the antenna has good circular polarization performance at the center frequency of 1.5GHz, the complex input impedance at the center of the dipole ($x=y=0$), which is shown in Figure 4.2 for the frequency range from 1.35GHz to 1.65GHz, is not matched with the 50 Ω transmission line. It is seen in this figure, the real part of the input impedance or the resistance, R_{in} , falls down gradually with the increasing of frequency, and it is about 50 Ω at the center frequency 1.5GHz. Plus, the input reactance, X_{in} , has a negative value which increases with the frequency, and reaches to zero at the frequency around 1.65GHz.

In order to eliminate the capacitive reactance at the center frequency of 1.5GHz and realize good axial ratio and return loss simultaneously, a CPS feeding line section is designed to match the antenna with the 50 Ω coaxial cable. By utilizing the simulation tool IE3D, the length of the dual L-shape strip is found to be $c=0.0845\lambda_0$ (16.9mm) with the width of $0.01\lambda_0$ (2mm). At the feeding point, the small squared patches with the length of $0.02\lambda_0$ (4mm) are formed in order to facilitate the linkage with the external connector in practical implementation.

4.2 Antenna Implementation and Measurements

In the design, the dual spiral-loop strip antenna, excited by a voltage source at center ($x=y=0$), was characterized using the IE3D software to achieve the CP radiation at the vertical z-axis and calculate the input impedance. It should be noted that the calculated results were obtained with the assumption of infinite

ground plane and perfect conductivity of the ground plane and metallic strip. These assumptions simplified the calculation and actually had little influence on the results especially on the input impedance. Then the layout of the antenna was exported from the IE3D for fabrication on the upper interface of RT6002 substrate by a milling machine. The implemented antenna sample was then placed above a square metallic ground plane with the area of $300 \times 300 \text{ mm}^2$ at a height about a quarter wavelength. A SMA connector was installed at the end of CPS to feed the antenna by a 50Ω coaxial cable. The experimental setup was the same as stated in Chapter 3. The return loss was measured by the network analyzer and the axial ratio and the radiation pattern was tested by the anechoic chamber. In the following sections, both of the calculated and measured results are presented and compared.

4.2.1 Return loss

Fig. 4.3 shows the calculated and measured return loss of the designed circularly polarized strip antenna in the frequency range of 1.35GHz to 1.7GHz. The black solid-line curve indicates the calculated result. The bandwidth with the return loss less than -10dB is about 6.7% and the calculated minimum return loss achieves -35dB at 1.51GHz. The small circles illustrate the measured results from the network analyzer. The -10dB return loss bandwidth is about 5.7%, which is a bit less than the calculated one. And the lowest return loss is -15dB at the frequency is shifted a bit to the right of 1.52GHz. It is seen that both the return

loss results agree with each other very reasonably. The slight discrepancy of the bandwidth and minimum return loss may be contributed by the unexpected capacitive and/or inductive effects at the CPS-to-probe transition.

Fig. 4.3 Calculated and measured results of the proposed antenna

4.2.2 Axial ratio

The simulated axial ratio is calculated by the full-wave simulation tool – IE3D, and the experimental results are obtained as the power ratio of two orthogonal electric field, E_{θ} and E_{ϕ} , measured by the microwave anechoic chamber. Figure 4.4 plots the calculated axial ratio in solid line and the measured one in small circles against frequency. The calculated and the measured values have a good agreement between them without visible frequency shift as shown in Figure 4.3

in the frequency range of 1.35GHz to 1.65GHz. It implies that the actual performance of the CP radiation produced by the proposed antenna is not seriously affected by the feeding line section and is basically dominated by the dual spiral-loop strip section. In Figure 4.4, the axial ratio bandwidths with $AR \leq 3\text{dB}$ are about 11% in the simulation and 10% in the measurement respectively. And the minimum calculated axial ratio is 0.23dB at 1.505GHz while the minimum measured one is 0.58dB at 1.50GHz. The reasons of the slight difference between them may be the finite ground plane used and that the antenna is not exactly parallel with the ground plane. And there may also exist some unexpected errors in fabrication and measurement.

Fig. 4.4 Calculated and measured return loss of the proposed antenna

4.2.3 Radiation pattern

Similarly to the measurement of the antenna axial ratio, the radiation patterns need to be measured in the microwave anechoic chamber. A linearly polarized horn antenna is placed horizontally to get the azimuth radiation pattern and then rotated 90° to obtain the elevation radiation pattern. The radiation patterns of the two perpendicular electric fields, E_θ and E_ϕ , at the central frequency of 1.5GHz are illustrated in Figure 4.5 (a) and (b), respectively. Since the antenna is symmetric with respect to the original point, the radiation pattern in the yz-plane can describe the antenna radiation performance quite well. Again, the solid lines are the calculated results and the circles depict the measured results. The 2D polar plots present a direct view of the radiation pattern. Due to the existence of the ground plane as a reflector, the radiation pattern of the antenna is unidirectional. Thus only the upper half of the polar plots are presented here. It is seen from the figures, the radiation pattern of the proposed antenna has a broad mainlobe without sidelobe. The shapes and the quantities of the radiation pattern for the two perpendicular electric fields are quite similar, which means a good circular polarization and a wide elevation range at this frequency. Moreover, the measured ones are well matched to the calculated ones in the broad elevated angle range of $-70^\circ \leq \theta \leq 70^\circ$. Outside this range, observable non-coincidence between them may be due to the finite ground plane used in the experiment.

Fig. 4.5 Radiation patterns on the yz-plane

Chapter 5 Conclusion and Recommendation

5.1 Conclusion

Printed wire antennas have received much attention in recent years due to their many advantages of low profile, easy fabrication, robust structure and cheap cost. Among them, the circularly polarized antennas have gained many wide applications in various modern wireless communications due to their good compatibility of the different polarized wave. In this thesis, the two kinds of non-resonant printed wire antennas with circular polarization fed by different transmission lines are simulated, designed, fabricated and measured. They all exhibit broadband circular polarization over a larger elevation angle range, and achieve good axial ratio and impedance matching simultaneously at the operation frequency.

At first, a low-profile printed hemispherical helical antenna is investigated comprehensively. The antenna possesses similar characteristics as the wired hemispherical helical antenna, and it is more robust and easy of impedance matching in the printed form. Numerical analysis of the performance of the proposed antenna is carried out by the full-wave simulation software IE3D. Intuitively speaking, the traveling wave current distribution along the antenna leads to a desired circular polarization of the radiated wave over a wide angular range. The antenna can be well matched with the 50Ω transmission line with a

S-shape strip at the center frequency. The antenna is found to have the impedance bandwidth of 6%, 3dB axial ratio bandwidth of 6%-7%, return loss greater than 20dB and a gain of about 9dB at the center frequency. The patterns of the antenna show a larger mainlobe in the upper half space with relatively small backlobes. These attractive features make the antenna suitable to be used as a GPS receiver.

Then a printed dual spiral-loop wire antenna above a ground plane is designed for circular polarization with broadband axial ratio and wide elevated angle. The two spiral loops are printed on both sides of a thin dielectric substrate and fed by a microstrip line. Extensive investigation is executed on the axial ratio and input impedance versus various antenna dimensions, and an optimized antenna sample is fabricated to verify the calculated results. The predicted and measured results are found in good agreement with each other, achieving the 3dB axial ratio bandwidth of ~15% and the -10dB return loss bandwidth of 6.7%. Moreover, the overall dimension of the antenna is reduced using the overlapped spiral arms by about ~24% compared with the original dual rectangular-loop wire antenna.

Finally, a CPS-fed printed dual spiral-loop strip antenna with circular polarization is proposed. This antenna is printed on the upper side of a RT6002 substrate, thus reduce the complexity of fabrication. It further reduces the whole

antenna dimension by a fraction of $\sim 13\%$ while keeping the similar performance of the microstrip-fed one. The antenna is simulated, implemented and tested. The calculated and measured results agree with each other quite well. This CPS-fed circularly polarized antenna believes to be very useful in exploring a new class of printed CP array using CPS feeding techniques.

5.2 Recommendations for future work

This thesis proposed several non-resonant printed CP wire antenna elements with different feedings. They all possess many attractive features such as compact size, easy fabrication, self-matching and good axial ratio over broad elevation angle range etc. Further studies can be carried on in the following directions.

5.2.1 Antenna array

Antenna array is usually used to increase the antenna radiation performances such as directivity and gain. The inherent advantage in geometry of the proposed printed wire antennas makes it be easily integrated to build up various planar antenna arrays. The axial ratio bandwidth may be further extended using several wideband techniques. For an example the antenna elements can be arranged orthogonal with each other and excited by source of equal amplitude but 90° out of phase. Moreover, a phase shifter can be added between two adjoining antenna elements to realize the beam steering as requested in many

applications [48].

5.2.2 Slot antenna with circular polarization

Slot antenna is the complementary form of the strip antenna. It is formed on the top interface of a dielectric substrate with a narrow slot cut on it. It is fed by a microstrip line on the lower interface through the slot-to-strip electromagnetic coupling as shown in Figure 5.1. It has many applications due to its attractive features such as low profile, efficiency, ease of feeding and fabrication. Since the radiation pattern of the slot antenna is the same as its complementary strip antenna, the proposed antennas can be implemented in the slotline form. The spiral-loop slot antenna is supposed to have high radiation efficiency with small transmission loss and it can be easily fed by coplanar strips or coplanar waveguide.

Fig. 5.1 Slot antenna fed by microstrip line

Author's Publications

[1] Y. Zhang and H.T. Hui, "A printed hemispherical helical antenna for GPS receivers", *IEEE Microwave and Wireless Components Letters*, vol. 15, pp.10-12, Jan. 2005

[2] Y. Zhang and L. Zhu, "CPS-Fed Printed Dual Spiral-Loop Strip Antenna with Circular Polarization", (submitted to *Microwave and Optical Technology Letters*)

[3] Y. Zhang and L. Zhu, "Printed Dual Spiral-Loop Wire Antennas for Broadband Circular Polarization", (submitted to *IEEE Transactions on Antennas and Propagation*)

Bibliography

- [1] John D. Kraus and Ronald J. Marhefka, “Antennas for all applications”, McGraw Hill, 1991.
- [2] “IEEE standard definitions for terms for antennas”, *IEEE Transactions On Antennas and Propagation*, 1983, AP-31.
- [3] William T. Whistler, “The microstrip dual folded dipole as a phased array element”, *IEEE Transactions on Antennas and Propagation*, 1983, AP25-5.
- [4] K. Tusnekawa, “High performance portable telephone antenna employing a flat-type open sleeve”, *IEICE Transactions on Electronics*, vol. E79-C, no. 5, 1996.
- [5] Jonhson J. H. Wang, “ Generalized moment methods in electromagnetics”, John Wiley & Sons, INC., 1991.
- [6] H. Nakano, Stephen R. Kerner and N.G. Alexopoulos, “ The Moment Method Solution for Printed Wire Antennas of Arbitrary Configuration”, *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 12, 1998.
- [7] H. Nakano, K. Hirose, and T. Suzuki etc. “Numerical analyses of printed line antennas”, *IEE Proceedings*, vol.136, 1989.
- [8] H. Nakano, H. Yasui and J. Yamauchi, “Numerical analysis of two-arm spiral antennas printed on finite-size dielectric substrate”, *IEEE Transactions on Antennas and Propagation*, vol. 50, 2002.
- [9] Constantine A. Balanis, “Antenna theory: analysis and design”, John Wiley & Sons, INC., 1997.

- [10] Aleksander Nesic, Sinisa Jovanovic and Ivana Radnovic, "Wideband printed antenna with circular polarization", *IEEE Transactions on Electromagnetic Compatibility*, 1999.
- [11] C.H. Chan, Y.X. Yu, K.M. Luk, " Numerical study of a proximity-coupled microstrip antenna", *IEEE Antennas and Propagation Society International Symposium*, vol. 4, 1997.
- [12] H. Nakano, G. Hirokawa, J. Yamauchi and K. Hirose, " Spiral antenna with coplanar strip line feed", *Electronics Letters*, vol. 28, no. 23, 1992.
- [13] N. Terada and K. Kagoshima, "Backfire/endfire radiation performance of quadrifilar helical antennas", *Electronics Letters*, 1991.
- [14] R.L. Li, V. F. Fusco, and H. Nakano, " Circularly polarized open-loop antenna", *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 9, 2003.
- [15] R. L. Li, V. F. Fuso, and H. Nakano, "Printed figure of eight wire antenna for circular polarization", *IEEE Transactions on Antenna and Propagation*, 2002.
- [16] H. Nakano, S. Okuzawa, and K. Ohishi etc., " A curl antenna", *IEEE Transactions on Antennas and Propagation*, vol. 41, NO. 11, 1993.
- [17] H. Morishita, K. Hirasawa and T. Nagao, "Circularly polarized wire antenna with a dual rhombic loop", *IEE Proc.-Microwave Antennas Propagation*, vol. 145, no. 3, 1998.
- [18] L. Zhu, and K. Wu, "Model-based characterization of CPS-fed printed

dipole for innovative design of uniplanar integrated antenna”, *IEEE Microwave and Guided Wave Letters*, vol. 9, no.9,1999.

[19] H.M. Chen, J.M. Chen, and P.S. Cheng etc., “Feed for dual-band printed dipole antenna”, *Electronics Letters*, vol. 40, no. 21, 2004.

[20] S. Matsuzawa and K. Ito, “Circularly polarized printed antenna fed by coplanar waveguide”, *Electronics Letters*, vol. 32, no. 32, 1996.

[21] W. C. Liu, “Broadband dual-frequency meandered CPW-fed monopole antenna”, *Electronics Letters*, vol.40, no. 21, 2004.

[22] Y. H. Suh, K. Chang, “A new millimeter-wave printed dipole phased array antenna using microstrip-fed coplanar stripline tee junctions”, *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 8, 2004.

[23] L. Boccia, G. Amendola and G. D. Massa, “A high-performance dual frequency microstrip antenna for global positioning system”, *IEEE Antennas and Propagation Society International Symposium*, vol. 4, 2001

[24] J. I. Ortigosa, N. Padros and M. F. Iskander, “ Comparative study of high performance GPS receiving antenna designs”, *IEEE Transactions on Antennas and Propagation*, vol. 45, 1997.

[25] R. A. Abd-Alhameed, P. S. Excell, “The complete surface current distribution in a normal-mode helical antenna”, *IEEE Transactions on Antennas and Propagation*, 1995.

[26] H. Kawakami, G. Sato, “Characteristics of modified GPS antennas”, *IEEE Transactions on Antennas and Propagation*, 1995.

- [27] Y. Kazama, "A quadrifilar helical antenna with a plastic loop", *IEEE Antennas and Propagation Society International Symposium*, 1994.
- [28] J. S. Colburn, Y. Rahmat-Samii, "Analysis of a square helix applicable to the personal satellite communication handset", *IEEE Antennas and Propagation Society International Symposium*, 1995.
- [29] J. Cardoso, A. Safaai-Jazi, "A spherical helical antenna", *IEEE Antennas and Propagation Society International Symposium*, 1993.
- [30] J. Cardoso, A. Safaai-Jazi, "Spherical helical antenna with circular polarization over a broad beam", *Electronics Letters*, 1993.
- [31] J. Cardoso, A. Safaai-Jazi, "Radiation characteristics of a spherical helical antenna", *IEEE Proceedings on Microwaves, Antennas and Propagation*, 1996.
- [32] H. T. Hui, K. Y. Chan, and E. K. N. Yung, "The low profile hemispherical helical antenna with circular polarization radiation over a wide angular range", *IEEE Transactions on Antennas and Propagation*, 2003.
- [33] H. T. Hui, E. K. N. Yung, and C. L. Law, "Design of a small and low-profile 2x2 hemispherical helical antenna array for mobile satellite communications".
- [34] L. Boccia, G. Amendola, and G.D. Massa, "A shorted elliptical patch antenna for GPS applications," *IEEE Antennas and Wireless Propagation Letters*, vol.2, 2003.
- [35] J. R. James and P. S. Hall, "Handbook of microstrip antennas", Peter, Peregrinus Ltd., 1989.

- [36] S. Okubo and S. Tokumaru, "Reactively loaded loop antennas with reflector for circular polarization ", *IEICE Transactions*, vol. J65-B, no. 8, 1982.
- [37] H. Morishita and K. Hirasawa, "Wideband circularly polarized loop antenna", *IEEE Antennas and Propagation Society International Symposium*, pp.1286-1289, 1994.
- [38] H. Morishita, K. Hirasawa and T. Nagao, " Wideband circularly-polarized rhombic loop antennas with different feed models", *IEEE Antennas and Propagation Society International Symposium*, pp. 194-197, 1995.
- [39] H. Scott and V. F. Fusco, "Polarization agile circular wire loop antenna", *IEEE Antennas and Wireless Propagation Letters*, vol.1, 2002.
- [40] B. Strassner and K. Chang, "Highly efficient C-band circularly polarized rectifying antenna array for wireless microwave power transmission", *IEEE Transactions on Antennas and Propagation*, vol.51, no.6, 2003.
- [41] M. Sumi, K. Hirasawa and S. Shi, "Two rectangular loops fed in series for broadband circular polarization and impedance matching", *IEEE Transactions on Antennas and Propagation*, vol.52, no.2, 2004.
- [42] E. Levine, S. Shtrikman and D. Treves, " Double-sided printed array with large bandwidth", *IEE Proc. Inst. Elec. Eng. Microwave Opt. Antennas*, vol.125, 1988.
- [43] F. Tefiku and C. A. Grimes, "Design of broad-band and dual-band antennas comprised of series-fed printed-strip dipole pairs", *IEEE Transactions on*

Antennas and Propagation, vol. 48, 2000.

[44] B. Strassner and K. Chang, "5.8-GHz circularly polarised dual-rhombic-loop travelling wave rectifying antenna for low power-density wireless power transmission applications", *IEEE Transactions on Microwave Theory Technology*, 2003.

[45] K. C. Gupta, R. Garg, and I. Bahl etc. "Microstrip lines and slotlines", Artech House, 1996.

[46] K. Y. Yazdandoost and R. Kohno, "Bow-tie antenna for UWB communication frequency", *IEEE Antennas and Propagation Society Symposium*, vol.3, 2004

[47] A. McCowen, "Efficient modelling of CPS and CPS-fed tapered slot antenna with a full wave 3D moment-method analysis", *Antennas and Propagation*, 2003

[48] L. Zhu, K. Kirino, I. Joishi, "Radiation characteristics of circularly polarized patch antennas mounted in a 2.45GHz wireless ID card system", *IEEE* 1996.

Appendices

Appendix A

Photograph of the printed hemispherical helical antenna

Appendix B

Photographs of the microstrip-fed printed dual spiral-loop wire antenna

Top-view

Bottom-view

Appendix C

Photograph of the CPS-fed printed dual-loop wire antenna