DESIGN OF Ku-BAND AXIAL MODE HELICAL ANTENNA

BY

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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

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DECLARATION

I declare that this thesis "*Design of Ku-band axial mode helical antenna*" was done by me and has never been presented elsewhere for the award of a Master Degree. It is the result of my own research work except for works that have been cited in the References.

....

Iliya Solomon Zakwoi Date

CERTIFICATION

This thesis titled *"Design of Ku-band axial mode helical antenna"* by Iliya Solomon Zakwoi (M.ENG/SEET/2007/1869) meets the regulation governing the award of the degree of Master of Engineering (M.Eng) of the Federal University of Technology, Minna and is approved for its contribution to scientific knowledge and literary presentation.

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ABSTRACT

Helical antenna designs for much higher frequencies have been a very challenging task for most antenna designers. This, therefore, necessitated the need to develop a simplified approach for the design of helical antenna which has frequency range between 12 GHz and 14 GHz. The purpose of this thesis, Design of Ku-band axial mode helical antenna, is to design helical antennas that could be utilized for much higher frequencies than the available WLAN and C-band frequencies. Design curves drawn using MATLAB for the design of Ku-band helical antenna, enables the prediction of the gain and bandwidth in relation to the axial length and pitch angle. The pitch angle was increased between 8° and 20° to achieve the objective of this thesis. The increase in pitch angle led to a small increment in axial length, thus necessitating the need to keep the pitch angle within the radiation zone for the axial mode helical antenna. Calculated values of the normalized axial length (in free space) L_λ lie between 0.5λ and 14λ which gave the maximum gain of 21.0295 dBi at an axial length of 14λ. Saturation in bandwidth of about 13% was obtained as against the 30% that was achieved for the C-band which is not so critical because many techniques aimed at maximizing bandwidths in communication systems have been developed. An improvement in gain was achieved in this design when compared to the gain obtained for the existing C-band designs.

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ABBREVIATIONS AND SYMBOLS

Abbreviations

VSWR	Voltage Standing Wave Ratio
SLH	Stub Loaded Helix
GA	Genetic Algorithm
BW	Bandwidth
BW_{Ku}	Bandwidth at Ku-band
AMSAT	American Meteorological Satellites
LHCP	Left-Hand Cross Polarization
RHCP	Right-Hand Cross Polarization
EME	Earth-Moon –Earth
QHA	Quadrifillar Helical Antenna
G/T	Figure of Merit
WLAN	Wireless Local Area Network
HFSS	High Frequency System Simulator
PDA	Personal Digital Assistant
NEC	Numerical Electromagnetic Code

Symbols

$\%BW$	Percent bandwidth for the C-band
$\%BW_{Ku}$	Percent bandwidth for the Ku-band
a_o	Maximum dimension of antenna
a	Radius of hemisphere
b	Radius of the outer conductor of coaxial wire
C	Helix Circumference
c	Speed of light in m/s^2
C_o	Constant coefficient for a given N-turn antenna
D	Diameter of Helix
d	Diameter of helix conductor
E	Total field pattern /Array factor
E_θ	Magnitude of electric field in θ
E_φ	Magnitude of electric field in φ
f_c	Center frequency (in GHz)
f_l	Lower frequency (in GHz)
f_u	Upper frequency (in GHz)
G	Gain of the helix at C-band
G_{Ku}	Gain of the helix at Ku-band (dBi)
h	Length of short straight wire between helix and the ground
K	Free space wave number
l_o	Length of One turn
L	Normalized axial length for C-band design (in lambda)
L_l	Normalized axial length for the Ku-band design (in lambda)
Lj	Axial length for C-band (in meters)

L_s Axial length for Ku-band (in meters)

m Order of transmission

N Number of turns of helix

n Number of isotropic point sources

P Relative phase velocity

P_f Forward or incident power

P_{Ku} Relative phase velocity for Ku-band

p_r Reflected power

r_w Radius of wire

S Turn Spacing of helix for C-band

S_1 Turn Spacing of the helix for Ku-band

x Increment in turn spacing

y Increment in axial length

α Pitch angle for C-band

α_1 Pitch angle for Ku-band

β Phase shift between successive elements

γ Increment in the C-band pitch angle

λ Wavelength for the C-band frequency

λ_{Ku} Wavelength at Ku-band frequency

CHAPTER ONE

1.0 INTRODUCTION

1.1 Antenna

An antenna is defined as the structure associated with the region of transition between a guided wave and a "free-space" wave, or vice versa. The adjective "free-space" is in quotation mark because in practice there always is some interaction with the surroundings. On transmission, an antenna accepts energy from a transmission line and radiates it into space and, on reception, gathers energy from an incident wave and sends it down a transmission line [Johnson, 1993].

A large variety of antennas have been developed to date; they range from simple structure such as monopoles and dipole to complex structures such as phased arrays. The particular type of antenna selected for a certain application depends upon the system requirements (both electrical and mechanical) and, to a lesser extent, upon the experience of the antenna engineer. Regardless of antenna type, all involve the same basic principle that radiation is produced by accelerated (or decelerated) charge.

In addition to receiving or transmitting energy, an antenna in an advanced wireless system is usually required to optimize or accentuate the radiation energy in some directions and suppress it in others. Thus the antenna must also serve as a directional device in addition to a probing device. It must then take various forms to meet the particular need at hand, and it may be a piece of conducting wire, an aperture, a patch, an assembly of elements (array), a reflector, a lens, and so forth.

For wireless communication systems, the antenna is one of the most critical components; a good design of the antenna can relax system requirements and improve overall system performance. A typical example is the television (TV) system for which the overall broadcast reception can be improved by utilizing a high-performance antenna.

The antenna serves to a communication system the same purpose that eyes and eyeglasses serve to human. The field of antennas is vigorous and dynamic, and over the last 60 years antenna technology has been an indispensable partner of the communications revolution. Many major advances that occurred during this period are in common use today; however, many more issues and challenges are facing us today, especially since the demands for system performances are even greater.

1.1.1 Types of Antenna

There are many types of antenna designed for various applications. They range from simple dipoles and monopoles to complex structured antennas. They include wire antennas, aperture antennas, microstrip antennas, array antennas, reflector antennas and lens antennas. Others include satellite antennas, beacon antennas, earth station antenna, conformal and low-profile antennas, their choice depending on the application desired.

Antennas deployed for satellite communications are high gain and directional. Utilizing high directivity (high gain) in the Ku band antenna compensates for the effect of rain attenuation, especially in geographic regions where rainfall is high.

(a) Wire Antennas

Wire antennas are familiar to the layman because they are seen virtually everywhere - on automobiles, buildings, ships, aircraft, spacecraft, and so on. There are various shapes of wire antennas such as a straight wire (dipole), loop, and helix. Loop antennas need not only be circular. They may take the form of a rectangle, square, ellipse, or any other configuration. The circular loop is the most common because of its simplicity in construction.

(b) Aperture Antennas

Aperture antennas may be more familiar to the layman today than in the past because of the increasing demand for more sophisticated forms of antennas and the utilization of higher frequencies. Antennas of this type are very useful for aircraft and spacecraft applications because they can be very conveniently flush-mounted on the skin of the aircraft or spacecraft. In addition, they can be covered with a dielectric material to protect them from hazardous conditions of the environment [Balanis, 2005].

(c) Microstrip Antennas

These consist of a metallic patch on a grounded substrate. The metallic patch can take many different configurations. However, the rectangular and circular patches are the most popular because of ease of analysis and fabrication, and their attractive radiation characteristics, especially low cross-polarization radiation. The microstrip antennas are low profile, conformable to planar and non planar surfaces, simple and inexpensive to fabricate using modern printed-circuit technology, mechanically robust when mounted on rigid surfaces, compatible with Microstrip Monolithic Integrated Circuit (MMIC) designs, and very versatile in terms of resonant frequency, polarization, pattern, and impedance. These antennas can be mounted on the surface of high-performance aircraft, spacecraft, satellites, missiles, cars, and even handheld mobile telephones.

(d) Array Antennas

Many applications require radiation characteristics that may not be achievable by a single element. It may, however, be possible that an aggregate of radiating elements in an electrical and geometrical arrangement (an array) will result in the desired radiation characteristics. The arrangement of the array may be such that the radiation from the elements adds up to give a radiation maximum in a particular direction or directions, minimum in others, or otherwise as desired. Usually, the term array is reserved for an arrangement in which the individual radiators are separate. However, the same term is also used to describe an assembly of radiators mounted on a continuous structure [Balanis, 2005].

(e) Reflector Antennas

The success in the exploration of outer space has resulted in the advancement of antenna theory. Because of the need to communicate over great distances, sophisticated forms of antennas had to be used in order to transmit and receive signals that had to travel millions of kilometers. A very common antenna form for such an application is a parabolic reflector. Antennas of this type have been built with diameters as large as 305 m. Such large dimensions are needed to achieve the high gain required to transmit or receive signals after millions of kilometers of travel. Another form of a reflector, although not as common as the parabolic, is the corner reflector .

(f) Lens Antennas

Lenses are primarily used to collimate incident divergent energy to prevent it from spreading in undesired directions. By properly shaping the geometrical configuration and choosing the appropriate material of the lenses, they can transform various forms of divergent energy into plane waves. They can be used in most of the same applications as are the parabolic reflectors, especially at higher frequencies. Their dimensions and weight become exceedingly large at lower frequencies. Lens antennas are classified according to the material from which they are constructed, or according to their geometrical shape.

1.1.2 Basic Antenna Parameters

The basic equation of radiation of antennas is expressed as

$$\dot{I} L = Q\dot{v} \quad (\mathrm{A\,ms^{-1}}) \tag{1.1}$$

$$L\frac{di}{dt} = Q\frac{dv}{dt} \tag{1.2}$$

where

$\dot{I}$ = time-change of current ($\mathrm{A\,s^{-1}}$)

L = length of current element (m)

Q = charge (C)

$\dot{v}$ = time change of velocity which equals the acceleration of the charge ($\mathrm{ms^{-2}}$)

Thus, radiation occurs in time changing current as well as the accelerated charge. For steady state harmonic variation, focus is laid on current while for the transient or pulses focus is laid on charge. Antennas appear to the transmission line from the circuit point of view as radiation resistance R_r. This resistance is not related to any resistance in the antenna itself but is a resistance coupled from space to the antenna terminals.

During transmission radiated power is absorbed by distant objects such as trees, buildings, the ground, the sky, and other antennas. During reception passive radiation from distant objects or active radiation from other antennas raises the apparent temperature of the radiation resistance R_r . This temperature, for loss less antennas has nothing to do with the physical temperature of the antenna itself but related to the temperature of distant object(s) that the antenna is facing.

1.2 The Helical Antenna

In 1946, a few months after Kraus joined the Faculty at Ohio State University, he attended an afternoon lecture on travelling-wave tubes by a famous scientist (Dr. Paul Raines) who was visiting the campus. An electron beam was fired down the inside of a long wire helix for amplification of waves travelling along the helix.

The helix is only a small fraction of a wavelength in diameter and acts as a guiding structure. After the lecture, Kraus asked the visitor if he thought a helix could be used as an antenna, to which the visitor replied in the negative. The finality of his answer set Kraus into thinking. If the helix were larger in diameter than in a travelling-wave tube, he felt that it *would have* to radiate in some way. He therefore determined to find out.

That evening in the basement of his home he wound a 7-turn helical coil of wire one lambda in circumfrence and fed it via coaxial line and ground plane from his 12 cm oscillator. It was thrilling to find that it produced a sharp beam of circularly polarized radiation off its open end. Next he wound other helices with larger and smaller diameters, noting little change in behaviour. Adding more turns however resulted in sharper beams. Although his invention /discovery came quickly, he realized then that much work would be required to fully understand this remarkable antenna.

Helical antenna consists of a single conductor or multiple conductors wound into a helical shape. Although a helix can radiate in many modes, the axial mode is of interest in this work. The axial mode provides maximum radiation along the helix axis, which occurs when the helix circumference is of the order of one wavelength. Higher order radiation modes are also possible. For example, when the helix dimensions exceed those required for the axial mode, a conical or multi-lobed pattern will result. Most helical antennas are designed to operate at frequencies between 2.4 GHz and 5 GHz limiting the applications to WLAN and C-band .

Generally, helical antennas are wound with a single conductor. However, a helix can be designed with bifilar, quadrifilar, or multifilar windings. An advantage of the backfire helix is that it does not generally require a ground plane because it minimizes blockage effects and improves reflector-antenna efficiency [Johnson, 1993].

1.2.1 Types of Helical Antenna

The helix is a basic three-dimensional geometric form. A helical wire on a uniform cylinder becomes a straight wire when unwound by rolling the cylinder on a flat surface. Viewed end-on, a helix projects as a circle; thus, it combines the geometric forms of a straight line, a circle and a cylinder. In addition, it also has handedness; it can either be left – or right-handed [Kraus and Marhefka, 2008].

There are two basic modes of propagation in helical antennas: the axial mode, and the normal mode. The axial mode implies that the gain is maximum along the axis of the helix, while the normal mode simply means that the gain is null along the axis of the helix. Various forms of helical antenna are enumerated in the following paragraphs.

(a) The Quadrifilar Helical Antenna

The antenna, also known as volute antenna, consists of two orthogonal fractional-turn (one-fourth to one-turn) bifilar helices excited in phase quadrature. Each bifilar helix is balun-fed at the top, and the helical arms are wires or metallic strips of resonant length wound on a small diameter, and has a large pitch angle. The ends of the helices are open-circuited at the base when *m*, being the order of transmission, is odd and short-circuited when *m* is even. When properly excited, the volute produces a very broad beamwidth with relatively low backlobes and good axial- ratio characteristics over a wide angular range. Since the volute is a resonant structure, the impedance bandwidth is narrow. Typically, the VSWR is less than 2:1 over a 3 to 5 percent bandwidth. Generally, a wider bandwidth can be achieved with larger-diameter wires for a given helix design. Although it is commonly used as a spacecraft antenna, the quadrifilar helix can also make an excellent ground station antenna. *Fig. 1.1* shows a schematic of the volute antenna.

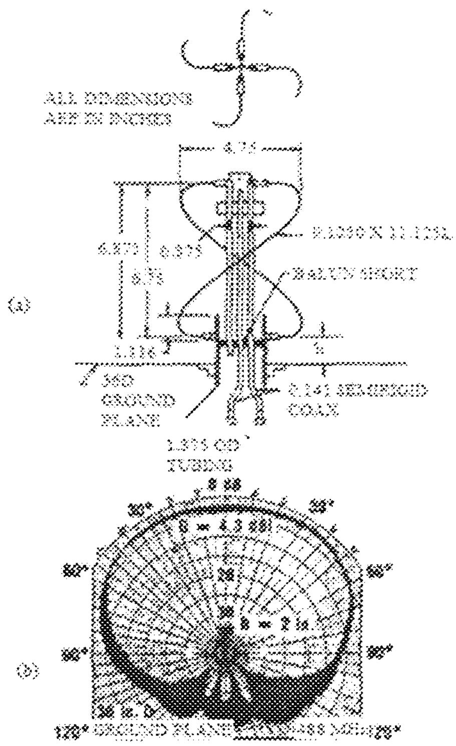

Fig. 1.1: (a) Half-turn, half-wavelength volute antenna
(b) Measured pattern at 488MHz [Johnson, 1993]

(b) The Spherical Helix Antenna

The traditional helix antenna consists of a helical winding on a cylindrical surface. Safaai-Jazi and Cardoso (1996) proposed a helical antenna that is formed on a spherical surface. The spherical helix consists of a helical winding with constant spacing between turns formed on a spherical surface. Their study indicated that the spherical helix has some interesting properties that are distinctly different from conventional helices over the range. Where the circumference of the sphere C_s lies between 0.75λ and 2.0λ, the spherical helix radiates in an endfire mode producing circular polarization. The gain of the antenna does not vary significantly with the number of turns used, unlike a cylindrical helix. The volume of the antenna is being held constant.

The unique characteristics of the spherical helix suggest that it might be a good candidate for use as a mobile antenna for low earth orbiting (LEO) satellite systems. Circular polarization over a broad beamwidth is highly desired but sorely lacking characteristic in current antenna designs used in LEO systems [Barts, 2003].

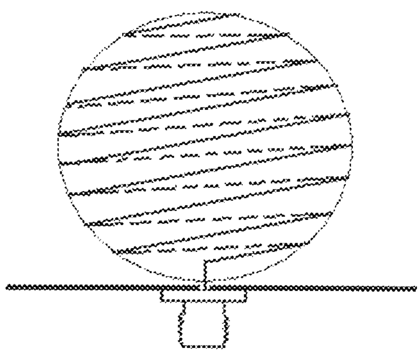

Fig. 1.2: Spherical helix antennas with ground plane

(c) Zig –Zag Antenna

Imagine a traditional helical structure that is flattened into a planar structure. The result would be a wire antenna formed in a zig-zag pattern, as shown in Fig 1.3. Cumming (1955) first investigated this antenna structure followed by Sengupta (1958). The zig-zag antenna is a form of traveling wave antenna that, when properly designed, produces a strong axial beam with very low side lobes. The gain of the antenna is a function of the Vee length (*2L*), the Vee angle (*2α*), and the number of Vee's. Results reported by Sengupta indicate that the zig-zag antenna has a usable bandwidth of approximately 10%, based on the pattern behavior. When the operating frequency is approximately 10% above the center frequency of the antenna, its pattern forms a split beam with a null on axis, similar to an axial mode helix operated in its second mode.

The front-to-back ratio and side-lobe characteristics of the zig-zag antenna are comparable to a Yagi-Uda design of similar length, but with a wider bandwidth due to the traveling wave nature of the antenna. The polarization of the zig-zag antenna is linear, as would be expected of a planar, endfire array. Sengupta's investigations were prompted by the desire to use the zig-zag antenna in a VHF radio-telescope array that was built at the University of Toronto. This antenna has little other application despite its features of high gain, simple construction, and relatively wide bandwidth [Barts, 2003].

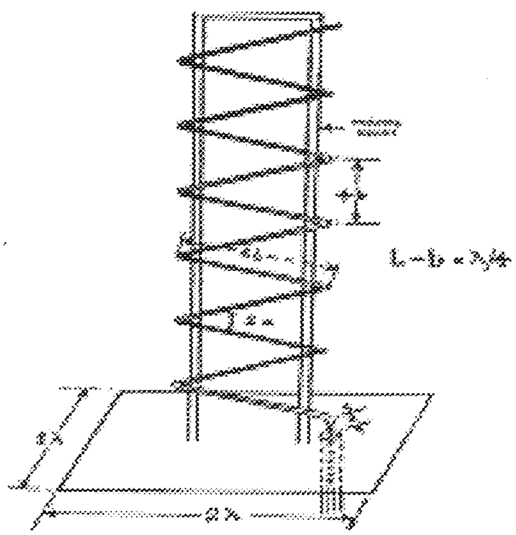

Fig. 1.3: Diagram showing the zig-zag antenna with feeding arrangement

(d) The Helicone Antenna

The helicone antenna is a full size helical antenna placed inside a large cylindrical horn. The helicone was developed by Carver as a variation of the helix with extremely low back- and side-lobes and increased directivity over a stand-alone helix. The helicone's bandwidth and axial ratio properties are superior to those of a conical horn excited from a circularly polarized waveguide operating in the TE11 mode.

The impedance behavior of the helicone is very similar to that of the helix alone, being predominately resistive with a small amount of reactance across the operating bandwidth. The extremely low back- and side-lobe level of the helicone makes it an attractive choice for radio astronomy where noise from the warm earth can increase the antenna noise temperature. Due to the low side-lobe levels, mutual coupling is minimal. Thus, using helicones in an array would be relatively straight forward [Barts, 2003].

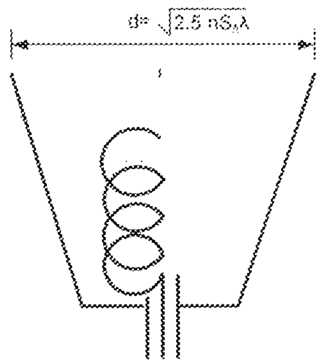

Fig. 1.4: The Helicone antenna

1.2.2 Some Helical Antenna Parameters

Helical antennas are characterized by the following parameters:

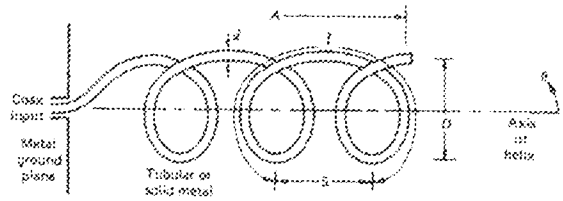

Fig. 1.5: Schematic of the helical antenna

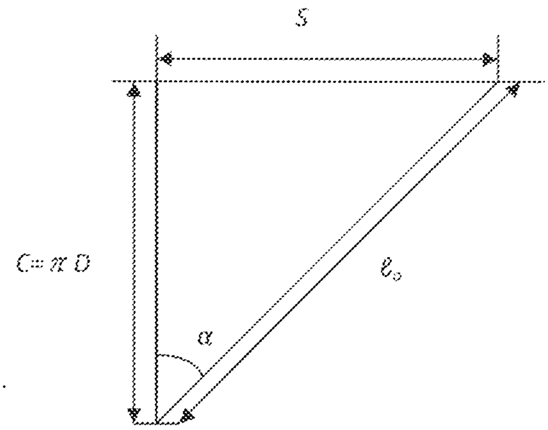

Fig. 1.6: Right Angle triangle showing the parameters of the helix

D= diameter of helix

C =circumference of helix= πD

S =spacing between turns in free space wavelengths (center to center)

α= pitch angle= $\tan^{-1}(S/\pi D)$

N= number of turns

L=Normalized axial length of helix =NS

d= diameter of helix conductor

ℓ_o= length of one turn =$\sqrt{[(\pi D)^2 + S^2]}$

1.2.3 Features of Helical Antenna

Kraus [1988] discovered that axial mode operation occurs when the circumference, C, of the helix is approximately one wavelength at the center frequency of operation and endfire axial mode operation is supported for approximately $0.75\lambda < C < 1.3\lambda$. The optimal pitch angle, α, was found to be approximately $10° < \alpha < 20°$ for axial mode operation. This corresponds to an inter-turn spacing of $0.17\lambda < S < 0.36\lambda$ at the center frequency of operation. The axial-mode helix's primary attributes are that it produces circular polarization and moderate gain over a wide (~50%) bandwidth. The current modes and phasing on the helix conductor affect the helix's properties.

The helix can be considered to be a continuous linear antenna carrying a traveling wave. Since the helical winding is periodic with a period equal to the turn spacing, the helix is considered to be a periodic structure. For a helical antenna to be in axial mode (end fire mode) with optimum performance in terms of gain, bandwidth and an axial ratio, the following conditions must be met [Kraus and Marhefka, 2008]:

- $0.8\lambda \leq C \leq 1.2\lambda$,
- $12° \leq \alpha \leq 14°$,
- $N \geq 4$

Due to the physical geometry of the helical antenna, it is extremely difficult to mathematically analyze the radiation properties, such as gain and input impedance. Therefore, investigation of the radiation properties is generally accomplished by experiments, analytical approximations, and numerical analyses [Wongpaibool, 2008].

1.3 Statement of the Problem

Over the years, designing the helical antenna to operate within higher microwave frequencies of about five gigahertz (5GHz) and above have been of great concern to most helical antenna designers, the reason being that existing equations and mathematical proof by Kraus, who is the founder of this remarkable antenna, and other authors show that stability at such higher frequencies are not feasible. As such most of the software are built having such conditions as basis for their operations, thereby making such designs almost impossible. In this thesis, attempt will be made to modify the pitch angles with a view to making them suitable for the Ku band application.

1.4 Aim

The aim is to show that helical antenna could be utilized to operate at higher frequencies such as Ku band (12~14) GHz by varying the pitch angle and axial length.

Analysis of the gain and bandwidth of the Axial Mode Helical antenna using standard engineering software like, Matlab, will be done to ascertain the viability of this helical antenna for the Ku band application.

1.5 Scope of the Project

In this thesis a modification of the existing mathematical equations on helical antenna will be done. A review of the axial mode helical antenna design parameters such as the pitch angle will be looked into. Effort will be made to vary the pitch angle with a view to making the design suitable for the Ku band frequency.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 The Stub Loaded Helix: A Reduced Size Helical Antenna

Barts (2003) established that the Stub-Loaded Helix (SLH) offers antenna performance comparable to the traditional axial mode helix but with a significant reduction in size. For the same number of turns, the SLH occupied a volume approximately one-third of a conventional helix. The performance of the SLH was explored through simulation and experiment.

A schematic diagram of the Stub Loaded Helix is shown in Fig. 2.1. The SLH consists of a helical winding around a central axis that is broken periodically by radially inward directed loading stubs. In the figure, four stubs per turn are shown, each stub positioned 90° with respect to the adjacent stubs. Because of the pitch angle of the helical winding, the stubs of a single turn do not lie in a common plane. The stubs are contiguous with the helix winding.

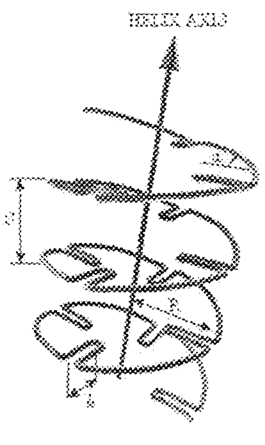

Fig. 2.1: Geometry of the Stub Loaded Helix antenna with important parameters R - radius of helix, α- pitch angle, S - turn-to-turn spacing, and l_s - stub depth [Barts 2003].

His motivation for developing the Stub-Loaded Helix geometry came from the desire to reduce the size of a conventional helix used in VHF/UHF satellite applications. At VHF/UHF wavelengths the physical dimensions of a conventional helix become large. Helical diameters in the order of 0.5 m are not uncommon and helix lengths can be in the order of several meters for high gain antennas. The physical size of these antennas requires large support structures and correspondingly large positioners. Any reduction in size of the helix is translated into cost reduction for the system as smaller support and positioning equipment will be required.

Barts enumerated numerous techniques that were attempted to reduce the helix size, and observed that most involved the use of dielectric materials with moderate or high permittivity to create a slow wave structure on which traveling wave will propagate and radiate. While some of these approaches have been successful they suffered from two deficiencies: Size reduction was achieved through the use of higher permittivity dielectrics which resulted in higher losses and lower radiation efficiency, and the cost of the dielectric materials is usually prohibitively high. The Stub-Loaded Helix however achieved its size reduction through the use of a unique and innovative geometry of the helix winding and did not require expensive materials that limit performance.

Important geometric parameters for the Stub Loaded Helix are the diameter, D, the pitch angle, α (related to the turn-to-turn spacing, S), the number of stubs per turn, Ns, the stub depth, l_s, and the number of turns, N. Typical values for these parameters are given in Table 2.1.

Table 2.1: Comparison of Conventional Helix and SLH Geometries Barts (2003)

Parameter	Conventional Helix	SLH
Circumference (C)	1λ	0.66λ
Diameter(D)	$0.318\ \lambda$	$0.210\ \lambda$
Radius (R)	$0.160\ \lambda$	$0.105\ \lambda$
Pitch angle (α)	$12° - 15°$	$8°$
Turn-to-turn spacing (S)	$0.21 - 0.26\ \lambda$	$0.093\ \lambda$
Volume/turn	$0.01689 - 0.0209\ \lambda^3$	$0.00322\lambda^3$
Depth of Loading Stub	-	$0.0795\ \lambda$

He summarized that, the Stub Loaded Helix geometry consists of a helical winding with periodic loading stubs around each turn. The circumference of the SLH was approximately 0.66λ and the depth of the loading stubs was approximately three-quarters of the helix radius, or 0.0795λ. The optimum pitch angle for the SLH was 8°. The one-third reduction in helix diameter and one-half reduction in turn-to-turn spacing characteristic of the SLH meant that for the same number of turns, the SLH occupies a volume one-third that of a conventional axial mode helix. This 3:1 reduction in size was a significant improvement. The size reduction did have a performance penalty, but the penalty was small compared to the improvement in size and may be of no consequence in the applications of interest.

2.2 Gain of the Axial Mode Helix Antenna

Emerson (1995) guessed that the axial-mode helix antenna is probably the most widely used circularly-polarized antenna, either in space or on the ground. He observed conflicting claims for the gain of the antenna; most amateur literature, and even many standard textbooks, quote gains which he said are far too optimistic. More realistic gain relationships are now available in the professional antenna journals, but are not well known in amateur circles.

His article summarized the most extensive numerical modeling calculations on the helical antenna ever performed. NEC-2 was used to model some 10,000 different helical antennas, systematically changing the physical parameters of the antenna and investigating the effect on gain and feed match. For each calculation, between 600 and 1400 segments were used to model an antenna; with frequent checks on the validity of the calculations. Some 3000 hours of networked Sparc workstation compute cycles were used for the study.

His modeling data were compared with results from the professional antenna literature. Reassuringly, the modeling gave results which are intermediate between published experimental and theoretical work. The maximum possible gains were up to 4 or 5 dB lower than those obtained by Kraus. The maximum gain increases much more slowly with increasing antenna length than the simple Kraus formula prediction.

Emerson found an empirical expression for the maximum possible gain G_{max} *of the helical* antenna as a function of its length L in wavelengths to be:

$$G_{max}(\text{dB}) = 10.25 + 1.22L - 0.0726L^2 \qquad (2.1)$$

This expression is only valid for lengths L between 2 and 7 wavelengths.

He also found an empirical expression for the turn radius R_{max} at which peak gain occurred as a function of length L in wavelengths to be:

$$R_{max} = 0.2025 - 0.0079L + 0.000515L^2 \qquad (2.2)$$

Again, this is only valid for lengths between 2 and 7 wavelengths.

His extensive modeling study is in good agreement with theory and measurement from the professional literature, all of which show that the gain obtained by Kraus for a helix is far too optimistic - by up to 4 or 5 dB. The modeling showed that, at a given value of turn spacing, the optimum turn radius for peak gain decreased slightly as the helix was made longer. The gain was almost independent of wire diameter, or of the presence of a short feed stub between the ground plane and the start of the helix. The resistance of wire used to construct the helix, even where several times worse than aluminium, had little effect on efficiency. A half-lambda square ground-plane was nearly as good as an infinite ground-plane. The use of radials, rather than a continuous ground-plane, gave a gain penalty of some 3.5 dB.

2.3 Enhancing the Gain of Helical Antennas by Shaping the Ground Conductor

Djordjevic and Zajic (2006) observed the size and shape of the ground conductor of axial mode helical antennas to have significant impact on the antenna gain. By shaping the ground conductor, they were able to increase the gain of a helical antenna by as much as 4 dB. They analyzed helical antennas above various types of ground conductors:

a) Antenna above infinite ground plane

b) Antenna above square ground conductor

c) Antenna above cylindrical cup

d) Antenna above truncated cone

Their explanation for the function of the cone was that it acts not only like a reflector (which collects and directs the energy spilled into the sidelobes), but also like a horn antenna that creates its own radiation pattern, which favourably interacts with the pattern of the helical antenna. Computed results were verified experimentally. The agreement between the computed and measured results was good and confirms that the adequate selection of the size and shape of ground conductor can enhance the gain of the helical antenna.

2.4 Helical Antenna Optimization Using Genetic Algorithm

Raymond (1999) formulated the Genetic Algorithm (GA) that was used to design helical antennas that provided a significantly larger bandwidth than conventional helices with the same size. Over the bandwidth of operation, the GA-optimized helix offered considerably smaller axial-ratio and slightly higher gain than the conventional helix. Also the input resistance remained relatively constant over the bandwidth.

He found out that, for nearly the same bandwidth and gain, the GA-optimized helix offered a size reduction of 2:1 relative to the conventional helix. The optimization was achieved by allowing the genetic algorithm to control a polynomial that defined the envelope around which the helix was wrapped. The fitness level was defined as a combination of gain, bandwidth and axial ratio as was determined by an analysis of the helix using Numerical Electromagnetic Code 2 (NEC2).

Genetic algorithms are useful for optimizing helical antennas to achieve desired performances such as high gain, low axial-ratio and wide bandwidth. Raymond observed that previous research on the optimization of helical antennas concentrated on building and testing large numbers of designs to find optimum solutions. According to him, integral based numerical methods are now available to solve helical wire antennas. These methods, in conjunction with modern optimization techniques such as genetic algorithms, allow engineers the freedom to create antennas that meet specific radiation characteristics.

The goal of the genetic algorithm in his research was to find an optimal shape for the helix that yields a low axial-ratio and high directivity over a wide bandwidth. Previous work on the helix presented new shapes and reported on their advantages and disadvantages. Genetic algorithms are used to find optimal solutions to a fitness function. Typically, Genetic Algorithms is used to maximize a single attribute; however, a helix requires optimization of several radiation properties. The genetic algorithm must maximize directivity and minimize axial-ratio over a wide bandwidth. This presents a trade-off problem and thus a compromise must be made.

Continuous control of the radius required a very large number of variables to optimize. The time required to optimize hundreds of variables was not feasible. A compromise was made to allow a discrete number of radius variables. An nth order polynomial allows $n+1$ discrete radius values to control the overall shape of the helix. Fitting the data in a least squares sense to a polynomial provided a simple equation to define the boundaries of the helix.

2.5 Helical Feed Antennas

Paul (2002) affirmed helical antennas to have long been popular in applications from VHF to microwaves requiring circular polarization, since they have the unique property of naturally providing circularly polarized radiation. One area that takes advantage of this property is satellite communications. Where more gain is required than can be provided by a helical antenna alone, a helical antenna could also be used as a feed for a parabolic dish for higher gains. The helical antenna can be an excellent feed for a dish, with the advantage of circular polarization. One limitation is that the usefulness of the circular polarization is limited since it cannot be easily reversed to the other sense, left-handed to right-handed or vice-versa.

Typical helix dimensions for an axial-mode helical antenna have a helix circumference of one wavelength at the center frequency, with a helix pitch of 12 to 14 degrees. The ground plane diameter is typically 0.94λ in diameter at the center frequency; but many other configurations have been used, including square plates, wire grids, cavities, and loops. The 3 dB beamwidth for a helix with n turns is approximately [Paul, 2002]:

$$BW_{3dB} = \frac{52}{C_\lambda \sqrt{n}\, S_\lambda} \tag{2.3}$$

where the circumference C_λ, and the turn spacing S_λ, are in wavelengths.

Almost all helical antennas have been made with uniform diameter and turn spacing. Suggestions for long helical antennas requiring variations in diameter and spacing over the length of the antenna have been made; just as optimized long Yagi-Uda antennas require variable element lengths and spacing for very high gain.

Some of the AMSAT satellites and others require more than 15 dB gain with circular polarization for good reception. Until someone finds an optimization that yields higher gain from a long helix, some other antenna type will be needed; a parabolic dish is often a good choice. While a large dish can provide gains upward of 30 dB, a small dish can easily provide the 20 to 25 dB gain needed for many satellite applications. The beamwidth of a small dish is broader than the beam of a large dish, making tracking less difficult. Of course, the dish needs a feed antenna, and a short helix was a good choice for circular polarization. A small offset dish is very attractive, since the feed blockage, which degrades small dish performance, is greatly reduced.

The calculated dish efficiency with the helix as a feed was very good, about 77%, at a center frequency of 2.4 GHz, with best *f/D* around 0.69, just about right for an offset-fed dish. Thus, we might expect a real efficiency greater than 60% feeding a reasonably sized (less than10λ) offset dish. A three-dimensional view of the radiation pattern, in Fig 2.2, shows a reasonably clean pattern with relatively small sidelobes; adjacent shades of grey have a difference in amplitude of 2 dB. The backlobes of most helical antennas, like the one in Fig 2.2, seem to have a twisted asymmetric shape.

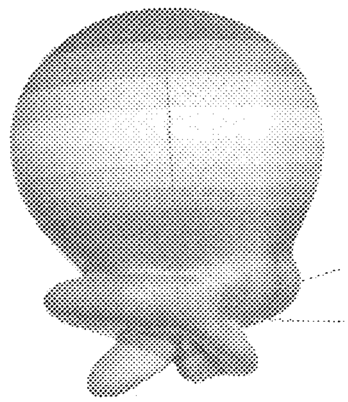

Fig 2.2: 4 Turn Helix at 2.4GHz [Paul, 2002]

Matching the impedance to 50 ohms over a broad bandwidth would be more difficult than simply matching it well for a ham band. A simple quarter-wave matching section with a Z ≈

84 ohms did the trick for a single band. The matching is often part of the helix: a quarter-wave of wire close to the ground plane before the first turn starts. It could also be on the other side of the ground plane, to separate impedance matching from the radiating element.

Circular polarization has two possible senses: right-hand (RHCP) and left-hand (LHCP). Since a helix cannot switch polarization, it is important to get it right. More important for a feed is that the sense of the polarization reverses on reflection, so that for a dish to radiate RHCP polarization requires a feed with LHCP. For Earth-Moon-Earth (EME), reflection from the moon also reverses circular polarization, so that the echo returns with polarization reversed from the transmitted polarization. A helical feed used for EME would not be able to receive its own echoes because of cross-polarization loss.

Paul affirmed the helical antenna as an excellent feed for circular polarization. Its broadband and dimensions, he said, are not critical and the patterns are well-suited to illumination of offset dishes. It is a particularly good feed for small offset dishes for satellite applications.

2.6 Central-Fed Hemispherical Helical Antenna

Chan et al (2001) observed antennas with circular polarization to have found wide applications in satellite communications due to their insensitivity to the ionospheric polarization rotation. The characteristic of a hemispherical central-fed helical antenna were investigated by experiment. Results for a 3-turn hemispherical helix indicated that circular polarization can be obtained over a wide angular range with relatively high gain of about 8 dB. The frequency bandwidth for a 3 dB axial ratio criterion was approximately 11%, with a nearly resistive input impedance of 163 Ω.

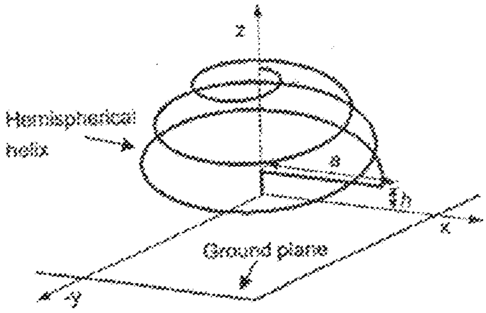

Fig.2.3: The geometry of the central-fed Hemispherical Helical Antenna

The curved portion of the thin wire was described by the following equation in the spherical co-ordinate system as proposed by Cardoso and Safaai-Jazi (1996).

$$\theta = cos^{-1}\left(\frac{\emptyset}{\pi N} - 1\right), \qquad \pi N \leq \emptyset \leq 2\pi N \qquad (2.4)$$

$radius = a$

where a is the radius of the hemisphere and N is a number equal to twice the number of turns of the helix. Note that eqn (2.4) describes only a right-handed helix. For a left-handed helix, the sign of the expression inside the bracket in eqn (2.4) should be reversed. The length of the short straight wire between the helix and the ground plane is denoted by h. The radius of the wire is r_w and is equal to the radius of the inner conductor of the coaxial line. The radius of the outer conductor of the coaxial line is b. The hemispherical helix was wound on the surface of a polystyrene hemisphere and was connected to a straight wire to a coaxial probe at the periphery of the hemisphere.

The authors believed the antenna to be very useful for array constructions. Magnitudes of E_θ and E_ϕ are very close to each other over a wide deviation angle from the main direction. This is the result of the wide angular coverage of circular polarization radiation of the antenna. These far- field characteristics accompanying the relatively high gain make this antenna a suitable candidate for mobile communications

A central-fed hemispherical helical antenna was intensively studied experimentally, and compared to the peripheral-fed configuration; it provided essentially the same radiation polarization patterns, but a significantly larger bandwidth and a better axial ratio. The antenna has potential applications in array constructions aimed at mobile satellite communications.

2.7 Quadrifilar Helical Antennas for Personal Satellite Terminals

Frank and Greg (2004) affirmed Quadrifilar Helical Antenna (QHA) an excellent choice for personal handsets that communicate with satellites. The QHA is capable of illuminating a considerable portion of the upper hemisphere. It provides omni-directional coverage in azimuth with an ability to tailor the pattern for the expected elevation angles to the satellite. The QHA is self sufficient without a counterpoise. Best performance was achieved when the antenna was isolated by itself, but that did not satisfy the needs of most mobile or personal applications. So, as in many antenna applications, the antenna is forced to work in a compromised manner.

Characteristically, they have learned to think of resonant antennas in terms of multiples of quarter-wavelengths. For the QHA, larger multiples tend to increase the gain at the peak of the beam. Quarter-wavelength element or filar length QHAs tend to have lower gain compared to half-wave filar antennas and exhibit narrower bandwidth. Higher multiple quarter-wavelength QHAs were made to direct the peak of beam for specific applications. In some cases beam widths less than hemispheric were desired. Higher multiples of quarter-wavelength elements tend to improve the front hemisphere to back hemisphere ratio. This was important in some applications to reduce the noise temperature of the antenna.

For today's communications products, the customers' applications tend to always require smaller, lighter, cheaper and better performance in a faster development time. Thus the antenna performance must be attempted for less than ideal size. For instance, in most applications, a 50-ohm characteristic QHA structure would have a larger diameter than is considered acceptable. A better antenna could be made if a three-quarter filar length could be used, but the overall antenna length may be too long for the customer preference. The real game seems to be to develop QHAs and other antennas to work well in spite of the imposed working conditions.

The antenna for personal or mobile earth terminals such as telephone handsets was subject to noise received by the antenna and the receiver added noise. The antenna noise temperature was the result of integrating the three-dimensional antenna pattern with the incremental noise temperatures over spherical space. Typically, the noise temperature varied with elevation angle. The receiver noise figure or noise temperature is an important factor in determining the performance. The G/T figure of merit demonstrates the contribution of antenna gain, antenna noise temperature, and receiver noise figure to the G/T figure of merit. Critical knowledge of system parameters can help determine the importance of setting adequate requirements for system link margin performance.

For personal or mobile earth terminals, one of the key performance parameters is the ratio of the receive antenna gain to the antenna noise plus receiver noise temperature ratio. This ratio is independent of modulation type or information bandwidth. This G/T ratio, normally expressed in decibels, was quite important for the communications system link budget. The general principles discussed in this paper have been used to develop a proprietary design for a satellite QHA aimed at the commercial market. The features and specifications are summarized in S-DMB (Hybrid version of Digital Multimedia Broadcasting) product specification sheet.

2.8 Dual-Band Planar Helical Antenna for WLAN Operation

A novel dual-band planar helical antenna was proposed by Yen et al (2009). The antenna was in the form of a rectangular helix, and was obtained by printing a plurality of linear metal strips on both sides of a dielectric substrate and then connecting the strips at their ends by shorting pins via-holes in the substrate. The total length of the rectangular helix controls the antenna's first or fundamental resonant frequency, and by adjusting the first turn spacing of the helix, the antenna's second resonant frequency can be adjusted. A constructed prototype with its first two resonant frequencies excited at about 2.4 and 5.2 GHz suitable for WLAN operation was presented and studied.

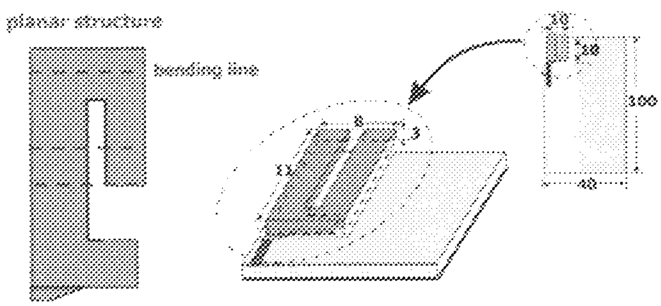

Fig 2.4: Dual-band operation in 2.4/5.2GHz WLAN bands

Fig 2.5 shows the measured return loss and simulated return loss. Two separate wide resonant modes at about 2.4 and 5.2 GHz were obtained. The simulated results were obtained from Ansoft HFSS, and good agreement between the measurement and the simulation was observed. From the measured results, the 10 dB return-loss bandwidths obtained are 208 MHz (2366–2574 MHz) and 252 MHz (5143–5395 MHz) for the lower and the upper modes, respectively, which cover the required bandwidths of the 2.4 and 5.2 GHz bands.

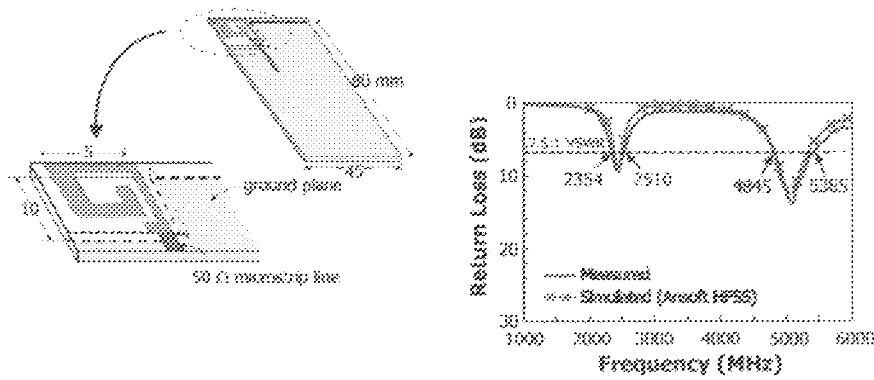

Fig 2.5: Dual-band spiral monopole for 2.4/5.2 GHz WLAN bands

The radiation characteristics were also studied. Fig 2.6 presents the measured peak antenna gain across the two operating bands. For the 2.4 GHz band, a stable peak antenna gain of about 2.9 dBi was measured. For the 5.2 GHz band, the peak antenna gain ranges from about 2.4 to 2.7 dBi.

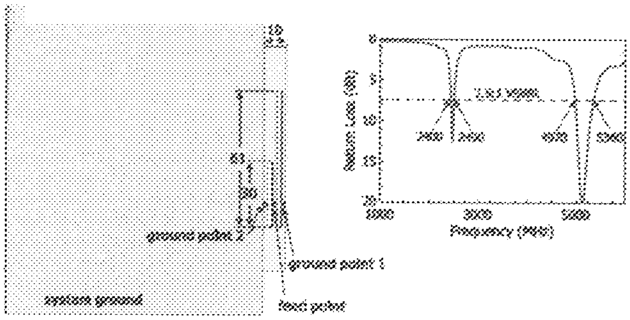

Fig 2.6: Antenna gain level in both 2.4 and 5.2 GHz about 6.0~7.0 dBi

A novel planar helical antenna with non-uniform turn spacing for dual-band operation was proposed, and a prototype printed and integrated on a grounded dielectric substrate about the size of the circuit board of a PDA device for 2.4/5.2 GHz WLAN operation was constructed and studied. Results show that two separate wide resonant modes at about 2.4 and 5.2 GHz were excited for the constructed prototype, and good radiation characteristics have been obtained.

2.9 The Spiro-Helical Antenna

Ghoreishian (1999) introduced a novel antenna made of a spiral wire wrapped into a larger helical shape. The geometry of this antenna, which was a doubly helical structure, was fully described by five independent parameters: two radial dimensions, two pitch angles, and the number of turns. Radiation properties of this antenna were examined both theoretically and experimentally. The Numerical Electromagnetic Code (NEC-2) was used to obtain simulation results.

A large number of cases with different radii, pitch angles, and numbers of *turns* were investigated. Results for far-field patterns, gain, axial ratio, and bandwidth were presented. The influences of parameters on radiation properties were examined. Several prototypes of the antenna were constructed and tested using an outdoor antenna range. Measured far-field patterns were presented over a wide range of frequencies. The measured and computed radiation patterns were in good agreement.

His study indicated that the proposed antenna provides circular polarization and high gain over a wide frequency range. For example, when the number of turns was 10, a gain of 11-14 dB, a boresight axial ratio of less than 3 dB, and a half-power beamwidth of about 40 degrees were achieved over a 30% bandwidth. The sidelobe level for most cases examined was better than 10 dB below the main beam. A unique advantage of this antenna is its much smaller size compared with a conventional helical antenna made of straight wire shaped into a helix, having about the same radiation characteristics, including gain, circular polarization, bandwidth, and side-lobe level. This new antenna occupied a volume about 3 times smaller than the conventional helix. This reduction in size, which in turn implied smaller weight and lower packaging and manufacturing costs, made the proposed antenna very appealing to many communications and aerospace applications.

2.10 The Radiation Properties of Electrically Small Folded Spherical Helix Antennas

Best (2004) considered the primary variables in the design of the antenna to be the number of helical turns and the number of helical arms. k is the free space wave number, that is $\left(\frac{2\pi}{\lambda}\right)$, while a_o is the maximum dimension of the antenna. The principal design objectives are to achieve self resonance, a low quality factor (Q), and a practical radiation resistance for small values of K_{a_0}. Designs were presented for K_{a_0} less than 0.5, where the antennas are self resonant, exhibiting efficiency in excess of 95%, a Q within 1.5 times the fundamental limit, and a radiation resistance near 50 Ω.

Relationship between the number of helical turns, the number of helical arms, and achieving self resonance at low frequencies was discussed. Radiation properties of the folded spherical antenna were presented. Antenna properties as a function of the number of helical turns and the number of helical arms were discussed.

Through appropriate selection of properties, it was demonstrated that the spherical folded helix could be made self resonant at small values of K_{a_0} with high efficiency. From a practical consideration, the limiting performance properties of any electrically small antenna are the antenna's quality factor and bandwidth. While the Q of these antennas is within 1.5 times the fundamental limit, the absolute value of Q can be high because of the small values of K_{a_0} at which these antennas are self resonant. Reducing the quality factor or increasing the bandwidth beyond these values while maintaining the same fixed volume typically required a trade-off in terms of reducing the antenna efficiency.

2.11 Coaxial-feed Axial Mode Hemispherical Helical antenna

Hui et al (1999) studied the wideband, high gain and circular polarization characteristics of conventional cylindrical helical antennas. From their investigations they found that spherical helical antennas can provide circular polarization over a wide beamwidth with radiation patterns free from sidelobes and low backlobe level. High gain of up to 9.5 dB is achievable with a 10-turn spherical helix. These are very significant differences from conventional cylindrical helical antennas.

They observed spherical helical antennas like cylindrical helical antennas as difficult to maintain in a vertical position over a flat ground plane. Their study of the hemispherical helical antenna was able to overcome this because hemispherical helical antennas, unlike the spherical helical antenna are only half as high. By winding the helix on the surface of a polystyrene hemisphere, the antenna rests very steadily on the ground plane. From their studies they found that the performance of the antenna is similar to that of a spherical helical antenna. They believe that the antenna would be useful for array construction because of its robust structure and no sidelobe patterns.

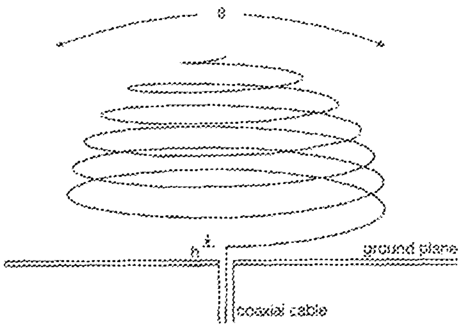

Fig 2.7: The geometry of the hemispherical helical antenna

The curved portion of the thin wire is described by eqn (2.5) in the spherical co-ordinate system by Cardoso and Safaai-jazi (1996) as

$$\theta = cos^{-1}\left(\frac{\emptyset}{\pi N} - 1\right) \qquad \pi N \leq \emptyset \leq 2\pi N \tag{2.4}$$

$radius = a$

where N is a number equal to twice the number of turns of the helix. Note that eqn (2.4) describes only a right-handed helix. For a left-handed helix, the sign of the expression inside the bracket in eqn 2.4 should be reversed. The length of the straight wire leading from the coaxial opening to the hemispherical helix is denoted by h. The radius of the wire is r_w and is equal to the radius of the inner conductor of the coaxial line. The radius of the outer conductor of the coaxial line is b. The hemispherical helix is wound on the surface of a polystyrene hemisphere and is connected to the coaxial line at the periphery of the hemisphere.

The simple coaxial-feed , axial mode, and 3-turn hemispherical helical antenna studied by Hui et al (1999) was found to foster a more stable structure than spherical helical antennas and provided extremely pure circular polarization over a broad beamwidth. The gain bandwidth product was approximately 33% while the peak gain was about 7.6 dB at C =1.33. Its input impedance showed a large reactive part over the axial mode frequencies.

2.12 Studies on a Novel Ellipsoidal Helical Antenna

Dongyu et al (2007) proposed and studied a novel ellipsoidal helical antenna as a special instance. The hemispherical helical antennas were first analyzed, their analysis indicating that the characteristics of a two-arm unit are better than those of a single-arm unit. Based on this, the ellipsoidal helical antenna, formed by changing the axial direction's dimension of the two-arm hemispherical helical antenna, was analyzed by the moment method with *curved* basic and testing function. The effects to VSWR (Voltage Standing Wave Ratio), gain, polarization and patterns by the axial direction's dimensions were investigated. The study provides dependable gist as to the choice of antenna format according to the practical requirements.

The two-arm hemispherical helical antenna evolved from the hemispherical helical antenna by winding another helical wire centro-symmetrically to the original one on the surface of a hemisphere.

2.13 Axial-Mode Patterns and Phase Velocity of Wave Propagation on Monofilar Helices

Kraus and Marhefka (2008) derived the first approximations for monofilar (single conductor) helical antenna radiating in the axial mode to have a single traveling wave of uniform amplitude along its conductor. By the principle of pattern multiplication, the far field pattern of a helix is the product of the pattern for 1 turn and the pattern for an array of n isotropic point sources. The number n equals the number of turns. The spacing S between sources is equal to the turn spacing.

They found out that when the helix is long (say $nS > 1$), the array pattern is much sharper than the single-turn pattern and hence largely determines the shape of the total far-field pattern. Hence, the approximate far –field pattern of a long helix is given by the array pattern. They assumed the far-field variation to be given by the array pattern or factor and that the difference between sources of the array is equal to the phase shift over one-turn length L for a single traveling wave, they found it possible to obtain a simple, approximate expression for the phase velocity required to produce axial-mode radiation.

They also discovered that if fields from all sources are in phase at a point on the helix axis ($\emptyset = 0$), radiation will be in the axial mode. For the fields to be in phase (ordinary end-fire condition) requires that

$$\psi = -2\pi m \tag{2.5}$$

where

m =0, 1, 2, 3..........m, being order of transmission

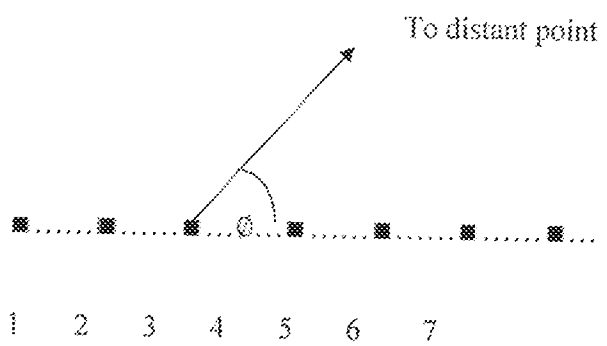

Fig 2.8: Array of isotropic sources, each source representing 1 turn of the helix

The minus sign in eqn (2.5) results from the fact that the phase of source 2 is retarded by $(2\pi L/p)$ with respect to source 1 and so on.

When $m = 1$

$$p = \frac{L}{S + 1} \tag{2.6}$$

From the triangle of Fig (1.6) page 13, eqn (2.7) can also be expressed as

$$p = \frac{1}{\sin\alpha + \left(\frac{\cos\alpha}{C}\right)} \tag{2.7}$$

Eqn (2.7) gives the variation in the relative phase velocity p as a function of the circumference C for in-phase fields in the axial direction. The variation for helices of different pitch angle is illustrated in Fig 2.9

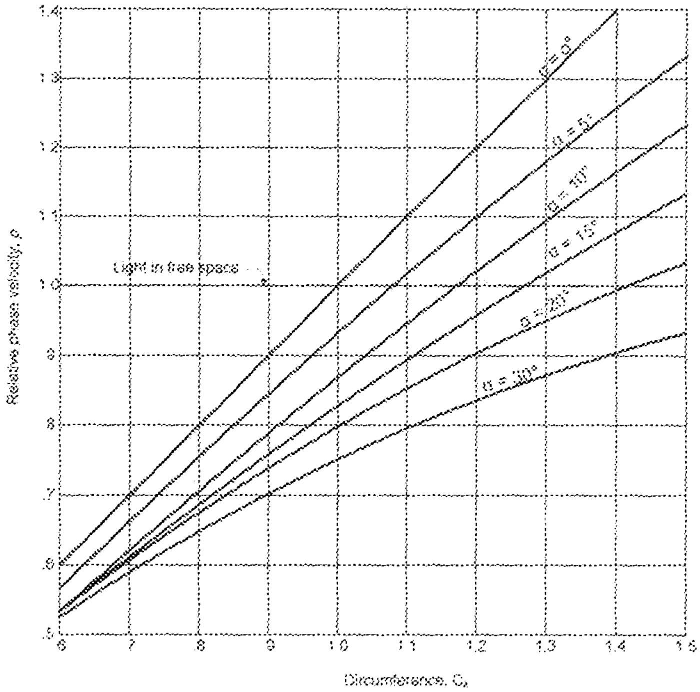

Fig 2.9: Relative phase velocity *(p)* for different pitch angles as a function of thehelix circumference *(C)* for the condition of in-phase fields in the axial direction [Kraus and Marhefka, (2008)]

2.14 Experiments on Triangular Copper Strip as Impedance Matching for 2.4-GHz Helical Antenna

Wongpaibool (2008) observed computer interconnection in the past using wire-line techniques, such as local area network (LAN), as inconvenient in most situations since computers must be within the range of cables. As network technology progressed, it became possible for computers to be connected together wirelessly. At present, computers are used to connect to the Internet through wireless LAN (WLAN) operating at 2.4-GHz frequency range.

The Internet is inevitable in our everyday lives. With portable computers and WLAN, the Internet can be accessed anywhere provided it is within the coverage area of a WLAN access point. The range of 802.11g WLAN is typically of the order of some hundreds of meters. He visualized theoretically the core of a helical antenna to be the air. However, an air-core helical antenna tends not to be durable in practice especially when the helical wire size is small.

The wire diameter used was 1.0 mm; it was supported on a polyvinyl chloride (PVC) tube to strengthen the antenna structure. The selected PVC tube had the outer diameter of 42 mm, which corresponds to the circumference C of 1.074 cm. The pitch angle was selected to be 12.41°. The total number of turns for the antenna was 16, and the reflector had the diameter of 18 cm. The helical wire was peripherally fed at the base by using Type-N female connector. To quantify the impedance mismatch, a measurable parameter related to impedance mismatch was required. The parameter he used was the return loss (dB) defined as

$$Return\ loss(dB) = -10\log_{10}\left(\frac{P_r}{P_f}\right) \tag{2.8}$$

With P_r and P_f as reflected power and forward or incident power respectively, at the point where return loss measured (for this experiment, it was the antenna feed point). The frequency range for return-loss measurement was from 2.36 GHz to 2.5 GHz, which covers the entire frequency range of WLAN.

Fig 2.10 shows a plot of return loss as a function of frequency at different strip lengths. The ideal case at which the input impedance of an antenna matches with the impedance of the transmission line, incident power was totally absorbed by the antenna, thus, no reflected power, and return loss equaled to $-\infty$ dB. However, from Fig. 2.10 without any kind of impedance matching, return loss became very poor and relatively flat across the measured frequency band. At frequency around 2.48 GHz, return loss became as poor as −7 dB. This corresponds to only 80 % of incident power being absorbed by the antenna.

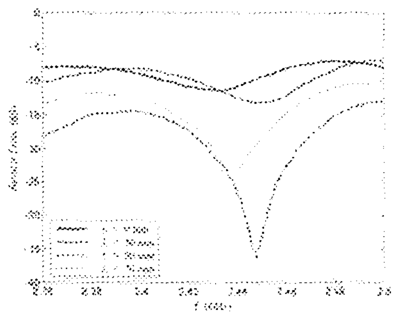

Fig 2.10: Return loss as a function of frequency at different strip lengths [Wongpaibool , 2008]

2.15 Design Curves for the Axial Mode Helical Antenna

Jennings (2002) in his paper obtained gain expression for the axial mode helical antenna which he applied to his design curves that made his design applicable to C-band. His design curves enable the prediction of the gain and bandwidth in relation to the axial length and pitch angle for any particular helical antenna with an axial length of between 0.5 lambda and 8 lambda. Fig 2.11 shows the relationship between the gain of a helical antenna and its axial length, as also represented by eqn (2.10). Fig 2.11 also shows the axial length for a given gain; thus, the gain for a given axial length may be obtained from this curve. The required pitch angle for a given axial length may then be found using Fig 2.12 or eqn (2.12). Fig 2.13 shows the bandwidth at optimum pitch angle (indicated by the red circles). It also shows the increase in pitch angle required for an increase in bandwidth. An increase in bandwidth resulted to a corresponding decrease in boresight gain. Pitch angles less than the optimum value are indicated by dotted lines.

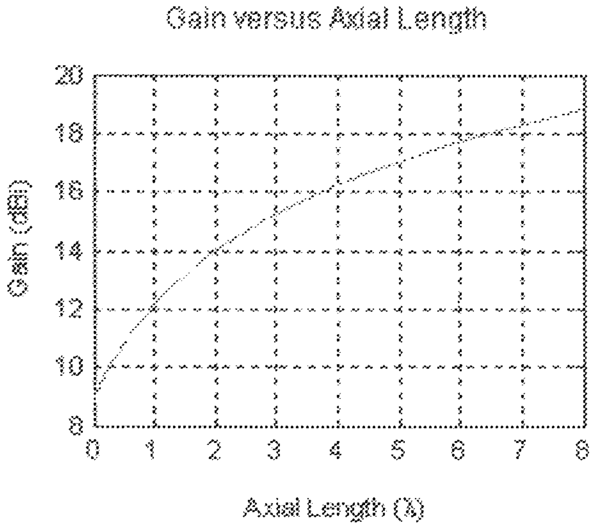

Fig 2.11: Gain (G) of a Helical Antenna as a function of axial length L [Jennings, 2002]

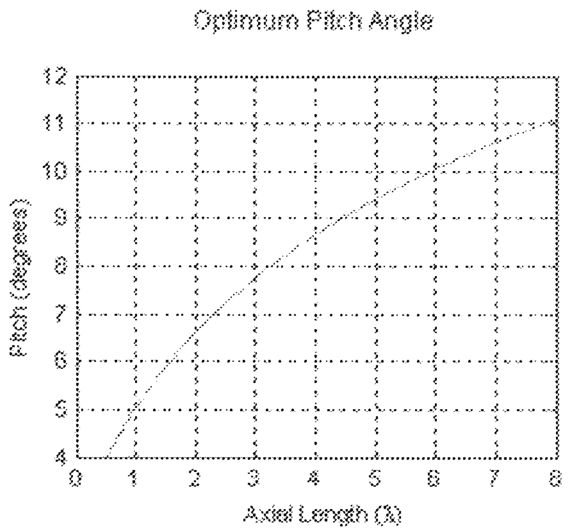

Fig 2.12: Pitch angle α versus Axial length L required for maximum gain [Jennings, 2002]

$$G = 10\log(8.5L + 7.75) \quad (2.10)$$

He obtained expression for the percent bandwidth, $\%BW$, as the difference between the upper and the lower frequencies normalized to the upper frequency f_u with f_l being the lower frequency

$$BW(\%) = \frac{f_u - f_l}{f_u} \quad (2.11)$$

$$BW(\%) = 2.5\,\alpha - 21.9 * \log(L) + 21 \quad (2.12)$$

Pitch angles less than the optimum value are indicated by dotted lines (for axial lengths 1.82 lambda, 4.13 lambda, 6 lambda and 8 lambda). Increased pitch angle resulted in improved VSWR. The bandwidth as shown in these curves was normalized to the upper frequency limit using eqn (2.11) and varies with pitch as shown in eqn (2.12). The dotted lines on the graph (for axial lengths of 0.5 lambda and 0.84 lambda indicate the saturation of bandwidth at high pitch angles.

2.16 Shortcomings of Reviewed works

Kraus and Marhefka (2008) established that for a helical antenna to be in axial mode (end fire mode) with optimum performance in terms of gain, bandwidth and an axial ratio, the circumference of the helix must lie between 0.8 and 1.2 of the wavelength thereby limiting the application to S and C bands. He also conditioned that the pitch angle α must lie between twelve degrees (12°) and fourteen degrees (14°) while the number of turns must not go below four (4). An improvement in terms of modifying Kraus's condition to expand the application for use in Ku band is possible.

Attempts to improve the performance of the conventional helix informed the need to alter the helix in discrete sections (tapering) which, according to literatures, presented a simpler design than the continuous shapes suggested by Kraus. It is difficult to achieve reduction in Voltage Standing Wave Ratio (VSWR) at the feed through tapering since the antenna designer has to go through this rigor to keep one of the helical antenna parameters constant while varying the others. Examples are, keeping the pitch angle*(α)* constant but varying both the turn spacing *(S)* and diameter *(D)*, or keeping diameter *(D)* constant and varying pitch angle *(α)* as well as turn spacing *(S.)* or keeping turn spacing *(S)* constant and varying both pitch angle *(α)* and diameter *(D)*. The simpler approach that can be adopted for matching is the use of a triangular copper strip matching technique for Ku band application" as suggested by Wongpaibool (2008).

CHAPTER THREE

3.0 MATERIALS AND METHODS

Antenna designers are always searching for ways to improve existing designs or introduce novel designs in order to achieve desirable radiation characteristics, reduce the size and weight, and thus make antennas more cost efficient. Axial ratio, gain, and bandwidth are some of the important properties which they concentrate on improving.

3.1 The Axial Mode Ku-band Helical Antenna

This chapter introduces the Ku-band axial mode helical antenna design in which the pitch angle $\alpha = \tan^{-1}(S/\pi D)$ will be varied in accordance with the proposal of Kraus and Marhefka (2008). Previous designs of the helical antenna were only limited to WLAN frequencies (2.4GHz) and C-band. Attempt is made in this work to modify the range in pitch angle for the axial mode helical antenna with a view of making it suitable for much higher frequencies, particularly the Ku-band.

The pitch angle for the Ku-band is called α_1 in this thesis. This will affect the axial length L of the axial mode helical antenna as obtained in Kraus and Marhefka (2008). The axial length for the Ku-band will be called L_x. Higher number of turns N known to increase the gain of the helical antenna will be utilized.

The Ku-band helical antenna will be analyzed computationally in terms of gain and axial length. Investigations of the pitch angle and design gain for Ku-band helical antenna will be carried out using Matlab simulation software.

The idea behind this design is to show that axial mode helical antenna can be utilized for higher frequencies, particularly the Ku band. Attention will be focused on the details of the axial mode helical antenna parameters which includes gain, bandwidth and pitch angle to maximize its performance.

3.2 General Properties of the Axial Mode Helix

The following are some important properties of the axial mode helical antennas:

- The circumference of the helix is of the order of one wavelength (which enable radiation with maximum power density in the direction of its axis)
- The circumference C is between 0.8 and 1.2 cm
- The pitch angle α is between 12° and 14°
- Number of turns N must be equal to or greater than four ($N \geq 4$)
- The impedance and radiation pattern do not change significantly over about one octave

3.3 Assumptions for the Ku-band Axial Mode Helical Antenna Design

The following are assumptions made in the design of Ku-band axial mode helical antenna:

- The Circumference $C = \pi D$ is equal to the wavelength λ of the frequency of operation f, where D is the diameter of the helix. That is, $C = \lambda$.
- The diameter of the helix; $D = \frac{\lambda}{\pi}$ (at the center frequency)

- Operating frequency: 12-14 GHz.
- Center frequency $f_o = \frac{f_l + f_u}{2} = \frac{12+14}{2} = 13$ GHz, where f_l =lower frequency and f_u =Upper frequency.
- Axial length range L_x: 1.2 - 32 cm
- The impedance bandwidth characteristics follow the gain bandwidth unless otherwise stated.
- The ground plane may be either flat or cupped in shape. In the case of a cupped ground plane the optimum dimensions are a diameter of 1 lambda and a depth of 0.2 lambda
- The diameter of the conductor may vary between 0.005 lambda and 0.05 lambda

3.4 Analysis of Ku-band Axial Mode Helical Antenna

The Ku-band axial mode helical antenna is a circularly polarized end-fire antenna that has characteristics determined by axial length L_x, pitch angle α_x, circumference C , and frequency of operation f.

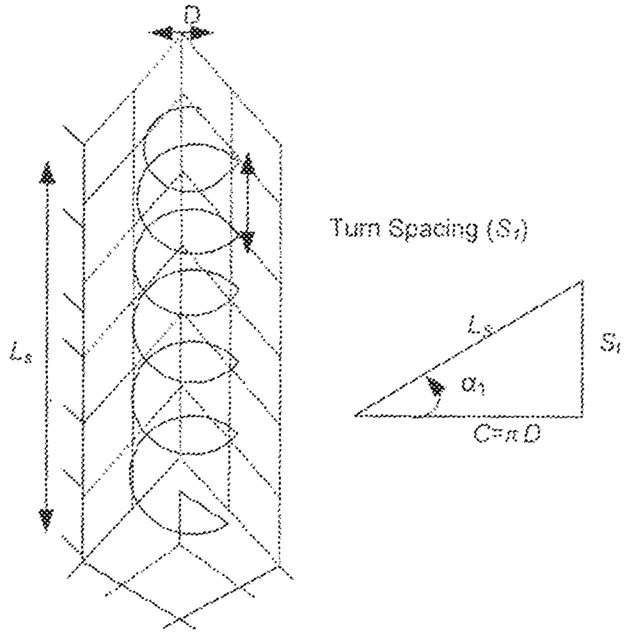

Fig. 3.1: The helical antenna showing the axial length L_g, turn spacing S_1 and the diameter D as well as the pythagoras relation indicating the pitch angle α_1 turn spacing S_1 and the circumference C.

It consists of an array of elements considered as number of turns representing isotropic point sources capable of radiating independently a circularly polarized wave, the more the number of turns the longer the axial length of the antenna and thus the higher the pitch angle. The design is based on the empirical relations for properties of the axial mode helix. Ku-band axial-mode helical antennas can have either a clockwise (right-handed) or counter-clockwise (left-handed) polarization. They can receive signals with any type of linear polarization, such as horizontal or vertical polarization.

In axial-mode operation, the winding sense of the coil determines its polarization, while the length of the coil determines how directional the antenna will be and its gain: longer antennas will be more sensitive in the direction in which they point. Fig 3.1 shows the axial length L_g, the pitch angle α_2 and the turn spacing S_2. As the pitch angle is increased the axial length L_2 also increases thus expectedly leading to higher gain.

There are two methods of analysis for the far-field pattern. The first method considers an N – turn helix as an array of N elements with an element spacing equal to S_1. The total field pattern E is obtained by the multiplication of the pattern in one turn of the helix by the array factor. The total field pattern E, as given by Kraus and Marhefka (2008), is

$$E = c_0 \frac{\sin(N\Psi/2)}{\sin\left(\frac{\Psi}{2}\right)} \cos\emptyset \tag{3.1}$$

Where $$c_0 = \left(\sin\frac{90}{N}\right) \tag{3.2}$$

is a constant coefficient for a given N-turn antenna

$$\Psi = kS_1\cos\emptyset + \beta \tag{3.3}$$

$\cos\emptyset$ = element pattern

$\frac{\sin(N\Psi/2)}{\sin\left(\frac{\Psi}{2}\right)}$ = Array factor for a uniform array of N equally-spaced elements (3.4)

The phase shift between successive elements is

$$\beta = -2\pi - \frac{\pi}{N} \tag{3.5}$$

The second method involves calculating the total field directly by integrating the contributions of the current elements from one end of the helix to another. The current is summed to be a travelling wave of constant amplitude.

3.5 Modelling of the Pitch Angle of the Ku-band Axial Mode Helical Antenna

The pitch angle of an axial mode helical antenna is given by Kraus and Marhefka (2008) as.

$$\alpha = \tan^{-1}\left(\frac{S}{\pi D}\right) \quad (3.6)$$

Modifying the pitch angle shown in the triangle of Fig 3.1 for the design of the Ku-band antenna gives Fig. 3.2:

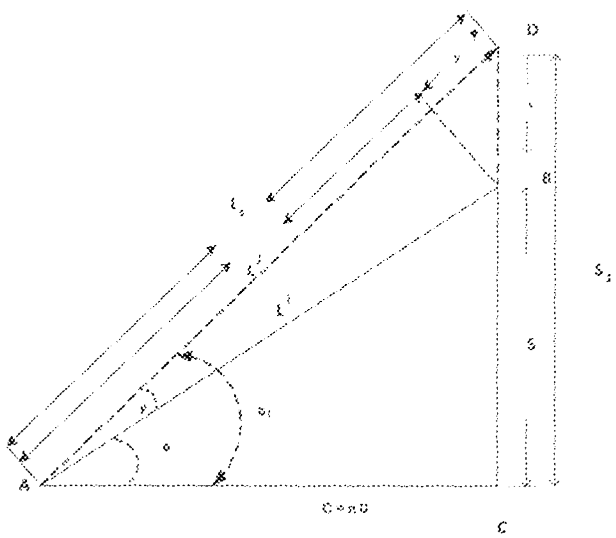

Fig. 3.2: Schematic representation of the increase in pitch angle with corresponding increment in axial length from L' to L_2 and turn spacing from S to S_1 while keeping the circumference fixed

Increasing the pitch angle improves the voltage standing wave ratio (VSWR), while keeping the circumference of the helix fixed. The increase in pitch angle controls the growth of the antenna in the z- direction, thereby increasing the length, because the larger the VSWR the larger the length, the larger the pitch angle and the smaller the return loss.

This is the principle used in the triangular copper strip matching for helical antennas by Wongpaibool (2008) where a short section (30mm) of helical wire was replaced at the feed point by a triangular copper strip that had same length (30mm) with the wire. The result did not give significant improvement in terms of return loss. This implies that short lengths of triangular copper strip as impedance matching is not effective. However, as the length of the triangular copper strip was increased return loss was improved (lower).

The pitch angle proposed by Jennings (2002) for the design of C-band axial mode helical antenna is denoted by α and is between $4°$ and $12°$. As shown in fig 3.2, as the pitch angle increases the axial length of the helix also increases. The design in this thesis increases the pitch angle α suggested by the work of Jennings with the variable γ, giving α_1 (proposed for this thesis), where $\alpha_1 = \alpha + \gamma$.

Table 3.1: Values of α_1 for γ increments.

α (degrees) Jennings (2002)	γ (degrees)	$\alpha_1 = \alpha + \gamma$ (degrees)
4	1	5
5	2	7
6	3	9
7	4	11
8	5	13
9	6	15
10	7	17
11	8	19
12	9	20

The range of the increment for the pitch angle is given as $1° \leq \gamma \leq 9°$ and the pitch angle proposed for this design is given by the range $5° \leq \alpha_1 \leq 20°$, as shown in Table 3.1. This range assumption is to ensure that the pitch angle does not go beyond the radiation limit of $20°$ for axial mode radiation of helical antennas as experimented by Kraus and Marhefka (2008).

L^j is the axial length of the helix used by Jennings (2002). But from Fig 3.2 increment in pitch angle also leads to small increment in the axial length L^j of the helix from L^j to L_s which is being used as the axial length in this thesis. Also, $L_s = L^j + y$, with y being small increment in the axial length of the helix. The turn spacing S also increases from S to S_1, and $S_1 = S + x$, with x being small increment in turns spacing.

From triangle ABC of fig (3.2)

$$\tan\alpha = \frac{S}{\pi D} \qquad (3.7)$$

$$\tan\alpha_1 = \tan(\alpha + \gamma) = \frac{S_1}{\pi D} = \frac{S+x}{\pi D} \qquad (3.8)$$

$$\alpha_1 = \alpha + \gamma = \tan^{-1}\left(\frac{S+x}{\pi D}\right) = \tan^{-1}\left(\frac{S_1}{\pi D}\right) \qquad (3.9)$$

$$\alpha_1 = \tan^{-1}\left(\frac{S}{\pi D} + \frac{x}{\pi D}\right) \qquad (3.10)$$

$$\tan(\alpha + \gamma) = \left(\frac{S}{\pi D} + \frac{x}{\pi D}\right) \qquad (3.11)$$

Using the expansion, we have

$$\tan\alpha_1 = \tan(\alpha + \gamma) = \frac{\tan\alpha + \tan\gamma}{1 - \tan\alpha\tan\gamma} = \left(\frac{S+s}{\pi D}\right) \tag{3.12}$$

The small increase in the axial length y is necessitated to ensure that the pitch angle is not too large and is kept within the radiation zone for helical antennas as experimented by Kraus and Marhefka (2008). If the increase is large, the pitch angle will be too large, exceeding the radiation limit for the axial mode helical antenna in free space; otherwise, the aims of the design will not be achieved since there will be no radiation in free space.

3.6 Modelling of the In-Phase field of Ku-band Axial Mode Helical Antenna

Variation in the relative phase velocity, p, of a wave propagating along the helical conductor as a function of the circumference, C, for in-phase fields in the axial direction is given by eqn (3.13) [Kraus and Marhefka, 2008].

$$p = \frac{1}{\sin\alpha + \frac{\cos\alpha}{C}} \tag{3.13}$$

As shown in fig 3.2, as the pitch angle increases the axial length of the helix also increases for the Ku-band helical antenna. And substituting $\alpha_1 = \alpha + \gamma$ for α in eqn (3.13), the relative phase velocity, p, is modeled for the Ku-band axial mode helical antenna as p_{Ku} thus,

$$p_{ku} = \frac{1}{\sin\alpha_1 + \frac{\cos\alpha_1}{C}} \tag{3.14}$$

Substituting $\alpha_1 = \alpha + \gamma$ into eqn (3.14), we have

$$p_{ku} = \frac{1}{\sin(\alpha+\gamma)+\frac{\cos(\alpha+\gamma)}{C}} \quad (3.15)$$

$$= \frac{1}{\frac{C\sin(\alpha+\gamma)+\cos(\alpha+\gamma)}{C}} \quad (3.16)$$

$$= \frac{C}{C\sin(\alpha+\gamma)+\cos(\alpha+\gamma)} \quad (3.17)$$

Introducing trigonometric expansion:

$$\sin(\alpha+\gamma) = \sin\alpha\cos\gamma + \cos\alpha\sin\gamma \quad (3.18)$$

$$\cos(\alpha+\gamma) = \cos\alpha\cos\gamma - \sin\alpha\sin\gamma \quad (3.19)$$

Substituting eqns (3.18) and (3.19) into eqn (3.17) we obtain

$$p_{ku} = \frac{C}{C(\sin\alpha\cos\gamma+\cos\alpha\sin\gamma)+(\cos\alpha\cos\gamma-\sin\alpha\sin\gamma)} \quad (3.20)$$

Simplifying gives

$$p_{ku} = \frac{C}{\cos\gamma(C\sin\alpha+\cos\alpha)+\sin\gamma(C\cos\alpha-\sin\alpha)} \quad (3.21)$$

Eqn(3.21) is the relative phase velocity for the Ku-band axial mode helical antenna which is the modification of the relative phase velocity (p) of waves propagating along the helical conductor as a function of the circumference (C) for in-phase fields in the axial direction with $\alpha_1 = \alpha + \gamma$, and α being the original pitch angle and γ being increase in the pitch angle. According to Kraus and Marhefka (2008), the increase in pitch angle by γ results to improved Voltage Standing Wave Ratio (VSWR) while keeping the circumference of the helix fixed. The increase in pitch angle controls the growth of the antenna in the z-direction thereby increasing the length of the helix. The VSWR is proportional to the length of the helix as a result the larger the VSWR the larger the length and the larger the pitch angle and eventually the smaller the return loss.

3.7 Design Curves for Ku-band Helical Antenna

The design curves for the Ku-band axial mode helical antenna enables the prediction of the gain and bandwidth in relation to the axial length and pitch angle for this particular helical antenna with a normalized axial length L_1 (in free space) between 0.5 λ and 14 λ.

3.7.1 Design Curve for the Gain versus Axial length of Ku-band helical Antenna

Jennings (2002) obtained expression for the gain G of the helix as a function of the axial length L (in free space) as seen in eqn (3.22).

$$G = 10\log(8.5L + 7.75) \tag{3.22}$$

For the C-band design by Jennings (2002), a center frequency f_c of 5.5 GHz with an axial length of the helix L' of 30 cm (0.3 m) was utilized. He obtained the normalized axial length L (in free space) that ranged between 0.5 λ and 5.5 λ for the C-band antenna as follows:

The C-band wavelength for a center frequency of 5.5GHz is

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{5.5\times10^9} = 0.0545\ \text{m}$$

For an axial length $L' = 0.3$ m

$$L = \frac{L'}{\lambda} = \frac{3.6}{0.6545} = 5.5045\,\lambda\ (L = \text{normalized axial length in free space})$$

This is the axial length (in free space) that gives the optimum gain of 17.5 dBi in Jenning's design.

From fig 3.2, increase in the pitch angle resulted to small increase in the normalized axial length (in free space) for the Ku-band helical antenna. Then the gain, using eqn (3.20), can be expressed as

$$G_{ku} = 10\log\,(8.5L_1 + 7.75) \qquad (3.23)$$

But

$$L_1 = \frac{L_s}{\lambda_{Ku}} \qquad (3.24)$$

where

L_1 is the free space axial length in terms of lambda

L_s is the length for the Ku-band design = 32 cm=0.32 m, while

λ_{Ku} is the Ku-band wavelength

Substituting eqn (3.24) into eqn (3.23) we obtain

$$G_{ku} = 10\log\,[8.5(\frac{L_s}{\lambda_{Ku}}) + 7.75] \qquad (3.25)$$

Simplifying eqn (3.25) we have

$$G_{ku} = 10\log\,[\frac{8.5L_s + \lambda_{Ku}(7.75)}{\lambda_{Ku}}] \qquad (3.26)$$

Eqn (3.26) is the expression for the gain for the Ku-band helical antenna modified from eqn (3.22).

3.7.2 Design Curve for the Percentage Bandwidth (BW %) versus pitch angle of Ku-band helical Antenna

For Ku-band helical antenna, the percentage bandwidth is obtained using eqns (3.27) and (3.28).

$$\%BW_{Ku} = \frac{f_u - f_l}{f_u} * 100 \qquad (3.27)$$

which is normalized to the upper frequency .

Jennings (2002) again related the percent bandwidth, pitch angle α and the axial length L using this equation

$$\%BW = 2.5\alpha - 21.9 * \log(L) + 21 \qquad (3.28)$$

As shown in fig 3.2, increase in the pitch angle results to small increase in the axial length of the Ku-band helical antenna , the percent bandwidth at Ku-band, the pitch angle α_1 and the axial length L_1 (in free space) are modified using eqn (3.29)

$$\%BW_{Ku} = 2.5\alpha_1 - 21.9 * \log(L_1) + 21 \qquad (3.29)$$

Substituting $\alpha_1 = \alpha + \gamma$ and $L_1 = \frac{L_2}{\lambda_{Ku}}$ into eqn (3.29) we have

$$\%BW_{Ku} = 2.5(\alpha + \gamma) - 21.9 * \log\left(\frac{L_2}{\lambda_{Ku}}\right) + 21 \qquad (3.30)$$

where

$\%BW_{Ku}$ is the percent bandwidth for the Ku-band design

α is the optimum pitch angle from Jennings (2002)

γ is the increment from the optimum pitch angle α by Jennings (2002)

Expanding eqn (3.30) we have

$$\%BW_{Ku} = 2.5\alpha + 2.5\gamma - 21.9 * \log\left(\frac{L_s}{\lambda_{Ku}}\right) + 21 \qquad (3.31)$$

Eqn (3.31) is the expression for percent bandwidth for the Ku-band design.

3.8 Ku-band Helical Antenna Design Using Design Curves

For the Ku-band design, a center frequency f_c of 13 GHz with an axial length of the helix L_s of 32 cm (0.32 m) is utilized. The normalized axial length L_λ (in free space) for the Ku-band antenna is obtained as follows:

The Ku-band wavelength is

$$\lambda_{Ku} = \frac{c}{f_c} \qquad (3.33)$$

where

c = speed of light = $3 * 10^8$ m/s

f_c = 13 GHz

$$\frac{3*10^8}{13*10^9} = 0.0231 \text{ m}$$

Input impedance R (ohms) = 109.1860

Axial Ratio AR (dimesionless) = 1.0294

Relative phase velocity ratio p = 0.6474

HPBW (in degrees):

Approximate = 30.5660

Numerical (from pattern) = 38.3200

FNBW (in degrees):

Approximate = 67.5979

Numerical (from pattern) = 75.1200

DIRECTIVITY:

Approximate (dimensionless) = 43.4131

Approximate (in dB) = 16.3762

Numerical (from pattern) (dimensionless) = 22.7037

Numerical (from pattern) (in dB) = 13.5610

The resulting helical antenna characteristics as obtained from Table; 4.1 and 4.2 are summarized as follows:

- Pitch angle 19.8 ≈ 20 degrees
- Normalized bandwidth: about 12.7046% ≈ 13%
- Axial length: 32cm (0.32m)
- Normalized axial length: 14 λ = 17turn
- Operating frequency: 12 GHz – 14 GHz
- Maximum possible gain: 21.0295 dBi
- Numerical directivity(from pattern) (dimensionless) = 22.7037

- Number of turns $N = 17$
- Circumference of loops C (in lambda) $= 0.7799$
- Spacing between turns S_1 (in lambda) $= 0.2799$
- Length (one-turn) L_c (in lambda) $= 0.8286$

CHAPTER FIVE

5.0 DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSIONS

The design curves used for the Ku-band helical antenna design provides a much better approach to realizing the helical antenna that was initially discovered by Kraus for much higher frequencies. It has proffered solution to the initial limitation of the use of the helical antenna to 2.4 GHz WLAN and the C-band frequencies. It can now be used as a tool by most antenna designers to achieve their design objectives. Jennings equations were modified in terms of the pitch angles and the axial lengths of the helical antenna. The modifications were meant to make the design suitable for the Ku-band frequency. Although as a result of the modification, the pitch angle falls out of the stable range of $12^\circ \leq \alpha \leq 14^\circ$ with about six degrees, it is however still within the region of radiation for helical antenna in free space which is a much desirable goal; careful variation in the axial length could help the helical antenna designer to achieve the desired stability.

The gain of 21.0295dBi value obtained from the computation is an improvement over the gain obtained from the C-band design by Jennings (2002), although the percent bandwidth for the Ku-band design is limited to only 13% which is however, not a critical situation since several techniques have been explored to improve bandwidth in various communications systems. The 13% in value of the saturation bandwidth for this frequency is in close agreement with the theoretical value of 14.2%.

5.1.1 Gains versus Axial Length

The graph of the gain versus axial length shown in Fig 4.1 is compared with that obtained by Jennings (2002) in Fig 2.12. As can be seen from Table 4.1, the gain obtained for the Ku-band design is higher than that of the C-band. This, thereby, shows that the helical antenna designed for the Ku-band has high capability in terms of the gain except for the limitation in bandwidth. The 21.0295 dBi value of maximum gain in this thesis was obtained from the Matlab computation in appendix A and Fig 4.1 respectively. The normalized bandwidth of 12.7046 percent is obtained from the Matlab computation in appendix C using eqn (3.31).

5.1.2 Axial Length versus Pitch Angle

The pitch angle γ of the Ku-band helical antenna designed is assumed to range from 8° to 20°. The axial length L_1 of the Ku-band has calculated values between 0.5 λ and 14 λ. The optimum pitch angle α_1 for a length of 14 λ is approximately 19.8 λ as obtained from the figure. This is the pitch required for a maximum gain as obtained from the graph. The 32cm axial length (L_s) for this thesis is obtained from the increment in pitch angle from 9.75 degrees in Jennings design for C-band to 19.8 degrees for the Ku-band design as seen in Figs (3.2 and 4.2). The normalized axial length(L_1) of 14 λ is obtained using the 32cm axial length (L_s) and the Ku-band wavelength of 0.0231m. this is the maximum axial length(L_1) that gives the 19.8 degrees optimum pitch angle.

5.1.3 Percent Bandwidth (BW %) versus the Pitch angle α_1

The modified equation from the work of Jennings (2002) for the computation of the percent bandwidth for the Ku-band design in this thesis is seen in eqn (3.31): the pitch angle was increased from $\alpha = 9.75^\circ$ to $\alpha_1 = 19.8^\circ$ by the factor γ as seen from this expression $\alpha_1 = \alpha + \gamma$. These values are both the optimum values for which the optimum gains were obtained where the range in values for pitch angles and normalized axial length are $8^\circ \leq \gamma \leq 20^\circ$ (assumed values) and $0.5\,\lambda \leq L_1 \leq 14\,\lambda$ (calculated values)

The required bandwidth of the antenna, normalized to the upper frequency limit of 14 GHz for the Ku-band, is 12.7046%. The optimum pitch angle, α_1, is approximately 19.8° at $L_1 = 14\,\lambda$. It can be seen that the optimum pitch angle α_1 falls out of the stable region of pitch angle α_1 between 12° and 14° with about six (6) degrees. Increasing the pitch angle caused a slight decrease in the bandwidth. In a bandwidth-limited application, the percentage bandwidth may be varied by changing the pitch, which may be kept within the stable region by varying the axial length. Matlab codes for the computation as well as eqn (3.31) used in obtaining Fig 4.3 are shown in Appendix C.

5.2 RECOMMENDATIONS

Much work has been completed in this thesis as was possible based on the given conditions. However, there are still a number of things that need to be done. The following are the recommendations for future work:

5.2.1 Bandwidth

Future work on the Design of Helical Antenna for much higher frequencies should focus more on ways to improve the bandwidth in order to make the antenna suitable for more applications. Data compression and polarization techniques are some techniques that can be explored to achieve this.

5.2.2 Security

The antenna structure needs to be adequately secured because the windings are fragile and need support in some cases. As a result, it becomes very necessary to safeguard it. Encapsulating the helical windings could be a way out. This can be done with the use of radome.

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APPENDIX A

MATLAB CODE FOR THE COMPUTATION OF GAIN AND AXIAL LENGTH OF KU-BAND HELICAL ANTENNA

```
% Script file:   Computation of the Gain and Axial Length of Ku-band
%                Axial Mode Helical Antenna
%
% Purpose:
%    To compute the gain and axial length of Ku-band axial mode helical
%    antenna, draw the curve and save the result.
%
% Record of revisions:
%      Date    Programmer      Description of change
%      ======  ============    =====================
%    07/01/10  S.Z. Iliya      Original Code
%
% Define variables:
%    GKu    -- Gain of the Ku-band antenna
%    L1     -- Axial Length
%

% Clear screen
clc;

% Insert an array of axial length L1
L1 = 0.5:0.1:20;
```

```
%  Calculate the gain (GKu) of the Ku-band antenna
GKu = 10*log10(8.5*L1+7.75);


%  Plot Curve
plot(L1, GKu, 'b');
xlabel ('\itL1 lambda (metre)');
ylabel ('\itGKu');
title('\itPlot of Gain (GKu) versus Axial Length (L1)');
legend('Gku Vs L1');
grid on;


%  Display results
fprintf('L1 = %5.0f\n', L1);
fprintf('GKu = %5.4f\n', GKu);
```

APPENDIX B

MATLAB CODES FOR THE COMPUTATION OF PITCH ANGLE AND AXIAL LENGTH OF KU-BAND HELICAL ANTENNA

```
% Script file: Computation of the pitch angle and the axial Length
%               of Ku-band Axial Mode Helical Antenna
%
% Purpose:
%    To compute the pitch and axial length of Ku-band axial mode helical
%    antenna, draw the curve and save the result.
%
% Record of revisions:
%    Date      Programmer      Description of change
%    ========  ==============  ==========================
%    07/01/10  S.Z. Iliya      Original Code
%
% Define variables:
%    alpha1    -- Pitch angle of the Ku-band antenna
%    L1        -- Axial Length1
%    GKu       -- Gain of the antenna
%


% Insert an array of the pitch angle (alpha1) of the Ku-band antenna
alpha1 = 6:1:21;


% Insert an array of gain (GKu)
GKu = 10:0.8:22;
```

```
% Calculate the axial length of the Ku-band antenna
L1=[10.^(GKu/10)-7.75]./8.5;

% Plot Curve
plot(L1,alpha1,'r');
xlabel ('\itL1 lambda (metre)');
ylabel ('\italpha1 (degree)');
title('\itPlot of pitch (alpha1) versus Axial Length (L1)');
legend('pitch (alpha1) Vs axial length (L1)');
grid on;

% Display results
fprintf('L1 = %5.0f\n', L1);
fprintf('GKu = %5.4f\n', GKu);
fprintf('alpha1 = %5.4f\n', alpha1);
```

APPENDIX C

MATLAB CODES FOR THE COMPUTATION OF PERCENT BANDWIDTH AND PITCH ANGLE FOR DIFFERENT AXIAL LENGTH

```
% Script file: Computation of the percentage bandwidch versus Pitch for different axial Length of Ku-band Axial Mode Helical Antenna

% Purpose:
% To compute the percentage bandwidth, the pitch angle for different axial length of Ku-band axial mode helical and save the result
%
% Record of revisions:
% Date Programmer Description of change
% ======== ============== ==========================
% 07/01/10 S.Z. Iliya Original Code
%
% Define variables:
% fu -- Upper frequency
% fl -- Lower frequency
% L1a -- Axial length for 0.5 lamda
% L1b -- Axial length for 0.84 lamda
% L1c -- Axial length for 1.82 lamda
% L1d -- Axial length for 4.13 lamda
% L1e -- Axial length for 6 lamda
% L1f -- Axial length for 8 lamda
% L1g -- Axial length for 10 lamda
% L1h -- Axial length for 12 lamda
```

```
%	L1i	-- Axial length for 13 lamda
%	L1j	-- Axial length for 14 lamda
%	percentBW   -- Percentage Bandwidth
%	alpha1 -- Pitch Angle

% Insert an array of pitch angle
alpha1 = 7:1:21;

% Input the values of axial length (L1)
L1a = 0.5;
L1b = 0.84;
L1c = 1.82;
L1d = 4.13;
L1e = 6;
L1f = 8;
L1g = 10;
L1h = 12;
L1i = 13;
L1j = 14;

% Calculate the percentBW
percentBWa = 2.5*alpha1 - 21.9*log(L1a) + 21;
percentBWb = 2.5*alpha1 - 21.9*log(L1b) + 21;
percentBWc = 2.5*alpha1 - 21.9*log(L1c) + 21;
percentBWd = 2.5*alpha1 - 21.9*log(L1d) + 21;
percentBWe = 2.5*alpha1 - 21.9*log(L1e) + 21;
percentBWf = 2.5*alpha1 - 21.9*log(L1f) + 21;
```

```
percentBWg = 2.5*alpha1 - 21.9*log(L1g) + 21;

percentBWh = 2.5*alpha1 - 21.9*log(L1h) + 21;

percentBWi = 2.5*alpha1 - 21.9*log(L1i) + 21;

percentBWj = 2.5*alpha1 - 21.9*log(L1j) + 21;


%  Plot Curve

plot(alpha1,percentBWa, 'r');

xlabel ('\itPitch (degrees)');

ylabel ('\itpercentBW');

title('\itPlot of percentBW versus pitch angle (alpha1)');

hold on;

plot(alpha1,percentBWb, 'b-.');

hold on;

plot(alpha1,percentBWc, 'g--');

hold on;

plot(alpha1,percentBWd, 'yo-');

hold on;

plot(alpha1,percentBWe, 'm-*');

hold on;

plot(alpha1,percentBWf, 'c-.');

hold on;

plot(alpha1,percentBWg, 'k-.');

hold on;

plot(alpha1,percentBWh, 'gx-');

hold on;

plot(alpha1,percentBWi, 'b');

hold on;
```

```
plot(alpha1,percentBWj,'r*-');
hold off;
legend ('0.5','0.84','1.82','4.13','6','8','10','12','13','14');

grid on;

%  Display results
fprintf('L1 = %5.0f\n', L1);
fprintf('percentBW = %5.4f\n', percentBW);
fprintf('alpha1 = %5.4f\n', alpha1);
```

APPENDIX D

MATLAB CODES FOR THE CALCULATION OF RADIATION CHARACTERISTICS

% Programmed by Bo Yang, 10/2002

% Edited by Iliya S.Z 12/5/2010

% Reference: "Antenna Theory: Analysis and Design. Second Edition, Constantine A. Balanis", Section 10.3.1, Helical Antenna

% --

% This program calculates the radiation characteristics of a helical antenna, both in the Normal mode and the Axial(End-fire) mode. The radiation characteristics which are calculated are:

% --

% I. Normal Mode

% a. Pitch angle alpha (in degrees)

% b. Axial ratio (AR)

% c. HPBW (in degrees)

% c. Directivity (dimensionless and in dB)

% ***

% II. Axial (End-Fire) Mode

% a. Pitch angle alpha (in degrees)

% b. Input impedance (ohms)

% c. Axial ratio (AR)

% d. Relative phas1e velocity ratio p

% e. HPBW (in degrees) (both approximate and numerical)

% f. FNNW (in degrees) (both approximate and numerical)

% g. Directivity (dimensionless and in dB) (both approximate and numerical)

% --

% Normalized radiation pattern of both modes are plotted. To get correct output, just follow the instructions below.

% Brief Manual %

% --

% 1.Choice of output

% Input 1 for Screen output

% Input 2 for File output

% 2.Choice of radiation mode

% Input 1 to select Normal mode

% Input 2 to select Axial (End-Fire) mode

% 3.Input

% --------

% a. Number of turns N

% b. Circumference of loops C (in lambda)

% c. Spacing between turns S (in lambda)

% ***

% For axial mode, also need to select end-fire mode:

% Input 1 to select Ordinary End-Fire

% Input 2 to select Hansen-Woodyard End-Fire

% 4.Output

% I. Normal Mode

% a. Pitch angle alpha (in degrees)

% b. Axial ratio (AR)

% c. HPBW (in degrees)

% c. Directivity (dimensionless and in dB)

% d. Plot the normalized radiation pattern (0 to -60 dB)

```
% II. Axial (End-Fire) Mode
% a. Pitch angle alpha (in degrees)
% b. Input impedance (ohms)
% c. Axial ratio (AR)
% d. Relative phase velocity ratio p
% e. HPBW (in degrees)
%    A. Approximate (use Equation 10-31)
%    B. Numerical (found from pattern)
% f. FNNW (in degrees)
%    A. Approximate (use Equation 10-32)
%    B. Numerical (found from pattern, set "zero" point to be less   than 1e-6)
% g. Directivity (dimensionless and in dB)
%    A. Approximate (use Equation 10-33)
%    B. Numerical (calculated from equation D0=4*pi*Umax/Prad)
% h. Plot the normalized radiation pattern (in dB: 0 to -60 dB)
% -----------------------------------------------------------------------
clear all;
close all;
clc
 fprintf('\n   *** NOTICE: This program uses "polar_dB.m" to plot the patterns!\n\n');
ang = 360;
%---Choice of output------------------------------------------------------
fprintf('Output device option: \n\tOption (1): Screen\n\tOption (2): File \n');
ERR = 1;
while(ERR ~= 0)
  DEVICE = str2num(input('\nOutput device = ','s'));
  if(DEVICE == 1)
```

```
        ERR = 0;
      elseif(DEVICE == 2)
        FILNAM = input('Input the desired output filename: ','s');
        ERR = 0;
      else
        fprintf('\nOutputting device number should be either 1 or 2\n');
      end
  end

  %---Choice of radiation mode---------------
  ERR = 1;
  while(ERR ~= 0)
    fprintf('\nSELECT RADIATION MODE:\n');
    fprintf('-----------------------\n');
    fprintf('(1) NORMAL MODE\n');
    fprintf('(2) AXIAL MODE\n\n');
    SELECT_mode = str2num(input('SELECT = ','s'));
    if or((SELECT_mode == 1), (SELECT_mode == 2))
      ERR = 0;
    end
end

%---Start of main program---
switch SELECT_mode,
  case 1
%---Normal mode-----------
  fprintf('\nInput:\n');
```

```
fprintf('---------\n');
    %---Input turn numbers---------------------------------
ERR = 1;
while(ERR ~= 0)
  N = str2num(input('Number of turns N = ','s'));
  N = round(N);
  if (isempty(N))
    fprintf('\n   *** ERROR: Please enter an integer!\n\n');
  elseif (N <= 0)
    fprintf('\n   *** ERROR: The number has to be greater than 0!\n\n');
  elseif (N > 10)
    fprintf('\n   *** WARNING: Large turn number may cause multi-lobe!\n\n');
    ERR = 0;
  else
    ERR = 0;
  end
end

%---Input circumference of loops----------------------------------------
ERR = 1;
while(ERR ~= 0)
  fprintf('\n   *** NOTICE: For Normal mode, C << lambda.');
  fprintf('\n               It is recommended that C/lambda <= 1/10.\n\n');
  C = str2num(input('Circumference of loops C (in lambda) = ','s'));
  if (isempty(C))
    fprintf('\n   *** ERROR: Please enter an number!\n\n');
  elseif (C <= 0)
```

```
        fprintf('\n   *** ERROR: The number has to be greater than 0!\n\n');
      else
        ERR = 0;
      end
    end


%---Input spacing between turns------------------------------------------
    ERR = 1;
    while(ERR ~= 0)
      fprintf('\n   *** NOTICE: For Normal mode, S << lambda.');
      fprintf('\n              It is recommended that S/lambda <= 1/20.\n\n');
      S = str2num(input('Spacing between turns S (in lambda) = ','s'));
      if (isempty(S))
        fprintf('\n   *** ERROR: Please enter a number!\n\n');
      elseif (S <= 0)
        fprintf('\n   *** ERROR: The number has to be greater than 0!\n\n');
      else
        ERR = 0;
      end
    end


%---Normal mode main program----------
%---Setup------------------------------
    step=0.1; % Step: accuracy control
    delta=1e-2; % To avoid sigularity in calculation
    angle=[0+delta:step:ang+delta];
    theta=angle*pi/180;
```

```
%---Pitch angle-----------
alpha=atan(S/C)*180/pi;


%---Axial Ratio---
AR=2*S/C;


%---Pattern-----------------------
L0=sqrt(C^2+S^2);
E=sin(theta); % Element factor
M=2*N; % Image due to ground plane
kesi=2*pi*(S*cos(theta));
AF=sin(M*kesi/2)./sin(kesi/2)/N; % Array factor
U=(E.*AF).^2; % Pattern mutiplicatin
[Umax,Index]=max(U);
U=U/Umax;
Umax=1;
U_dB=10*log10(U);


%---HPBW(From pattern)---------
HP_dB=(1/sqrt(2));
for i=Index:length(U)
  if U(i)<HP_dB
    HPBW=angle(i)+angle(i-1)-2*angle(Index);
    break;
  end
end
```

```
%---Directivity-------------------------
   integrand=U.*sin(theta)*step*pi/180;
   Prad=2*pi*sum(integrand(1:round(length(integrand)/2)));
   D0=4*pi*Umax/Prad;
   D_dB=10*log10(D0);

%---Create output-------------
if(DEVICE == 2)
  fid = fopen(FILNAM,'w');
else
  fid = DEVICE;
end
%---Echo input parameters and output computed parameters----------
fprintf(fid,'\nHELIX: NORMAL MODE:\n');
fprintf(fid,'\nInput parameters:\n------------------');
fprintf(fid,'\nNumber of turns N = %3.0f',N);
fprintf(fid,'\nCircumference of loops C (in lambda) = %6.4f',C);
fprintf(fid,'\nSpacing between turns S (in lambda) = %6.4f',S);
fprintf(fid,'\nLength (one-turn) L0 (in lambda) = %6.4f',sqrt(C^2+S^2));
fprintf(fid,['\nLength (',num2str(N),'-turn) LN (in lambda) = %6.4f'],N*sqrt(C^2+S^2));

fprintf(fid,'\n\nOutput parameters:\n-------------------');
fprintf(fid,'\nPitch angle alpha (in degrees) = %6.4f',alpha);
fprintf(fid,'\nAxial Ratio AR (dimensionless) = %6.4f',AR);
fprintf(fid,'\nHPBW (in degrees) = %6.4f',HPBW);
fprintf(fid,'\nDirectivity(approximate) (dimensionless) = 1.5');
fprintf(fid,'\nDirectivity(approximate) (in dB) = 1.7609');
```

```
fprintf(fid,'\nDirectivity(numerical from pattern) (dimensionless) = %6.4f',D0);
fprintf(fid,'\nDirectivity(numerical from pattern) (in dB) \t= %6.4f',D_dB);
fprintf(fid,'\n\n');
if(DEVICE == 2)
  fclose(fid);
end
%---Plot normalized radiation pattern(in dB:-60-0dB)----------------------
polar_dB(angle,U_dB,-60,0,4,'-');
title('Normalized Radiation Pattern of Normal Mode Helical Antenna(in dB)');


case 2
%---Axial(End-fire) mode
   fprintf('\nInput:\n');
   fprintf('---------\n');


%---Input turn numbers--------------------------------
   ERR = 1;
   while(ERR ~= 0)
      N = str2num(input('Number of turns N = ','s'));
      N = round(N);
      if (isempty(N))
         fprintf('\n   *** ERROR: Please enter an integer!\n\n');
      elseif (N <= 0)
         fprintf('\n   *** ERROR: The number has to be greater than 0!\n\n');
      else
         ERR = 0;
      end
```

```
  end


%---Input circumference of loops-----------------------------------------
  ERR = 1;
  while(ERR ~= 0)
    fprintf('\n   *** NOTICE: To achieve nearly circular polarizaion, it is');
    fprintf('\n              recommended that 3/4 <= (C/lambda) <= 4/3.\n\n');
    C = str2num(input('Circumference of loops C (in lambda) = ','s'));
    if (isempty(C))
      fprintf('\n   *** ERROR: Please enter an number!\n\n');
    elseif (C <= 0)
      fprintf('\n   *** ERROR: The number has to be greater than 0!\n\n');
    else
      ERR = 0;
    end
  end


%---Input spacing between turns-----------------------------------------
  ERR = 1;
  while(ERR ~= 0)
    fprintf('\n   *** NOTICE: To achieve nearly circular polarizaion, it is');
    fprintf('\n              recommended that S/lambda is approximately 1/4.\n\n');
    S = str2num(input('Spacing between turns S (in lambda) = ','s'));
    if (isempty(S))
      fprintf('\n   *** ERROR: Please enter an number!\n\n');
    elseif (S <= 0)
      fprintf('\n   *** ERROR: The number has to be greater than 0!\n\n');
```

```
        else
            ERR = 0;
        end
    end
  %---Axial(End-fire) mode main program---
  %---Setup-----------------------------------
    step=0.1; % Step: accuracy control
    delta=1e-2; % To avoid sigularity in calculation
    angle=[0+delta:step:ang+delta];
    theta=angle*pi/180;

 %---Choice of End-Fire mode---------------
 ERR = 1;
 while(ERR ~= 0)
    fprintf('\nSELECT END-FIRE MODE:\n');
    fprintf('-------------------------\n');
    fprintf('(1) ORDINARY END-FIRE\n');
    fprintf('(2) HANSEN-WOODYARD END-FIRE\n');
    fprintf('(3) END-FIRE (p=1)\n\n');
    SELECT_end = str2num(input('SELECT = ','s'));
    if (SELECT_end== 1)|(SELECT_end == 2)|(SELECT_end == 3)
      ERR = 0;
   end
end

%---Pitch Angle-------
alpha=atan(S/C)*180/pi;
```

```
%---Input Impedence----
R=140*C;

%---HPBW(Approximate)-----
HPBW_app=52/(C*sqrt(N*S));

%---FNBW(Approximate)----
FNBW_app=115/(C*sqrt(N*S));

%---Directivity(Approximate)---
D_app=15*N*C^2*S;
D_app_dB=10*log10(D_app);

%---Axial Ratio---
AR=(2*N+1)/(2*N);

%---Pattern-----
L0=sqrt(C^2+S^2);
if SELECT_end == 1
%---Ordinary end-fire----------
  p=L0/(S+1);
elseif SELECT_end == 2
%---Hansen-Woodyard end-fire----
  p=L0/(S+(AR));
else
%---End-fire (p=1)----
  p=1;
```

```
end
kesi=2*pi*(S*cos(theta)-1.0/p);
U=(sin(pi/(2*N))*cos(theta).*sin(N/2*kesi)./sin(kesi/2)).^2;
Umax=max(U);
U=U/Umax;
Umax=1;
U_dB=10*log10(U);


%---Numerical results from pattern---
if (SELECT_end ~= 3)
%---HPBW(From pattern)---------
imax=1;
HP_dB=(1/sqrt(2));
for i=1:length(U)
   if U(i)<HP_dB
      HPBW=angle(i)+angle(i-1);
      break;
   end
end
%---FNBW(From pattern)----------
for i=1:length(U)
   if U(i)<1e-4 % set "zero" point to be less than 1e-4
      FNBW=angle(i)+angle(i-1);
      break;
   end
end
else
```

```
%---HPBW(From pattern)---------
HP_dB=(1/sqrt(2));
[temp,imax]=max(U);
end
for i=imax:-1:2
   if U(i)<HP_dB
      HPBW=angle(imax-i)+angle(imax-i+1);
      break;
   end
end
%---FNBW(From pattern)----------
for i=imax:-1:2
   if U(i)<1e-4 % set "zero" point to be less than 1e-4
      FNBW=angle(imax-i)+angle(imax-i+1);
      break;
   end
end
%---Directivity(From pattern)-------
integrand=U.*sin(theta)*step*pi/180;
Prad=2*pi*sum(integrand(1:round(length(integrand)/2)));
D0=4*pi*Umax/Prad;
D_dB=10*log10(D0);
%---Create output-------------
if(DEVICE == 2)
  fid = fopen(FILNAM,'wt');
else
  fid = DEVICE;
```

```
end


%---Plot normalized radiation pattern(in dB:-60-0dB)------------------------
polar_dB(angle,U_dB,-60,0,4,'-');
if SELECT_end == 1
   title('Normalized Radiation Pattern of Ordinary End-Fire Helical Antenna(in dB)');
elseif SELECT_end == 2
   title('Normalized Radiation Pattern of Hansen-Woodyard End-Fire Helical Antenna(in dB)');
else
   title('Normalized Radiation Pattern of End-Fire (p=1) Helical Antenna(in dB)');
end


%---Echo input parameters and output computed parameters---------
if SELECT_end == 1
   fprintf(fid,'\n HELIX: ORDINARY END-FIRE MODE:\n');
elseif SELECT_end == 2
   fprintf(fid,'\n HELIX: HANSEN-WOODYARD END-FIRE MODE:\n');
else
   fprintf(fid,'\n HELIX: END-FIRE MODE (p=1):\n');
end
fprintf(fid,'\nInput parameters:\n-----------------');
fprintf(fid,'\nNumber of turns N = %3.0f',N);
fprintf(fid,'\nCircumference of loops C (in lambda) = %6.4f',C);
fprintf(fid,'\nSpacing between turns S (in lambda) = %6.4f',S);
fprintf(fid,'\nLength (one-turn) L0 (in lambda) = %6.4f',sqrt(C^2+S^2));
fprintf(fid,['\nLength (',num2str(N),'-turn) LN (in lambda) = %6.4f'],N*sqrt(C^2+S^2));
```

```
if (SELECT_end == 1)|(SELECT_end == 2)|(imax == 1)
fprintf(fid,'\n\nOutput parameters:\n-------------------');
fprintf(fid,'\nPitch angle alpha (in degrees) = %6.4f',alpha);
fprintf(fid,'\nInput impedance R (ohms)) = %6.4f',R);
fprintf(fid,'\nAxial Ratio AR (dimesionless) = %6.4f',AR);
fprintf(fid,'\nRelative phase velocity ratio p = %6.4f',p);
fprintf(fid,'\n\nHBPW (in degrees):');
fprintf(fid,'\n   A. Approximate(10-31) = %6.4f',HPBW_app);
fprintf(fid,'\n   B. Numerical(from pattern) = %6.4f',HPBW);
fprintf(fid,'\n\nFNBW(in degrees):');
fprintf(fid,'\n   A. Approximate(10-32) = %6.4f',FNBW_app);
fprintf(fid,'\n   B. Numerical(from pattern) = %6.4f',FNBW);
fprintf(fid,'\n\nDirectivity:');
fprintf(fid,'\n   A1. Approximate(10-33) (dimensionless) = %6.4f',D_app);
fprintf(fid,'\n   A2. Approximate(10-33) (in dB) = %6.4f',D_app_dB);
fprintf(fid,'\n   B1. Numerical(from pattern) (dimensionless) = %6.4f',D0);
fprintf(fid,'\n   B2. Numerical(from pattern) (in dB) = %6.4f',D_dB);
fprintf(fid,'\n\n');
else
   fprintf(fid,'\n\n-----------------------------------------------------------------------------\n');
   fprintf(fid,'BAD DESIGN! MAXIMUM IS NOT AT 0 DEGREES!\n');
   fprintf(fid,'PLEASE SEE THE PLOTTED RADIATION PATTERN FOR DETAILS.\n');
end
if(DEVICE == 2)
  fclose(fid);
end
end
```

```
%---End of main program---
figure (2)
title('Linear plot of power pattern')
hold on
plot(theta(1:1800),U_dB(1:1800))
plot(-1*theta(1:1800),U_dB(1:1800))
grid on
hold off
axis([-3.2 3.2 -50 0])
xlabel('theta (rad)')
ylabel('Radiation Intensity (dB)')
```

*** NOTICE: This program uses "polar_dB.m" to plot the patterns!

Output device option:

Option (1): Screen

Option (2): File

Output device = 1

SELECT RADIATION MODE:

----

(1) NORMAL MODE

(2) AXIAL MODE

SELECT = 2

Input:

Number of turns N = 17

*** NOTICE: To achieve nearly circular polarizaion, it is
recommended that 3/4 <= (C/lambda) <= 4/3.

Circumference of loops C (in lambda) = 0.7799

*** NOTICE: To achieve nearly circular polarizaion, it is
recommended that S/lambda is approximately 1/4.

Spacing between turns S (in lambda) = 0.2799

SELECT END-FIRE MODE:

----

(1) ORDINARY END-FIRE

(2) HANSEN-WOODYARD END-FIRE

(3) END-FIRE (p=1)

SELECT = 1

HELIX: ORDINARY END-FIRE MODE:

Input parameters:

Number of turns N = 17

Circumference of loops C (in lambda) = 0.7799

Spacing between turns S (in lambda) = 0.2799

Length (one-turn) L0 (in lambda) = 0.8286

Length (17-turn) LN (in lambda) = 14.0863

Output parameters:

Pitch angle alpha (in degrees) = 19.7427

Input impedance R (ohms)) = 109.1860

Axial Ratio AR (dimesionless) = 1.0294

Relative phase velocity ratio p = 0.6474

HBPW (in degrees):

A. Approximate(10-31) = 30.5660

B. Numerical(from pattern) = 38.3200

FNBW(in degrees):

A. Approximate(10-32) = 67.5979

B. Numerical(from pattern) = 75.1200

Directivity:

A1. Approximate(10-33) (dimensionless) = 43.4131

A2. Approximate(10-33) (in dB) = 16.3762

B1. Numerical(from pattern) (dimensionless) = 22.7037

B2. Numerical(from pattern) (in dB) = 13.5610