DESIGN OF A QUASI-LUMPED ELEMENT RESONATOR ANTENNA WITH MAGNETIC COUPLING FEEDING

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UNIVERSITI SAINS MALAYSIA

2013

DESIGN OF A QUASI-LUMPED ELEMENT RESONATOR ANTENNA WITH MAGNETIC COUPLING FEEDING

By

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Thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

December 2013

DEDICATION

This work is dedicated to:

God Almighty

My wife: Bolatiwa

And my children: Jesutofunmi, Oreoluwa and, Anjolaoluwa

ACKNOWLEDGMENT

I would like to sincerely appreciate my supervisors, Associate Professor Dr. Mohd Fadzil Ain and Professor Zainal Arifin Ahmad for their commitments. Dr. Fadzil Ain has this potential to devise a research topic with feasible foreseeable future results output. I sincerely desire his extent of patience and attributes of not given up on a student even in a hopeless situation until he turns them to a success story. He has demonstrated this attribute a number of times. Professor Zainal Ahmad is not different either. He has a sense of humor that naturally dissipates and diffuses your pressure and stress in no time as you discuss the challenges of your work with him with much concern. He responds to questions, discussion, and review of write-ups either article or thesis almost instantly. They are simply amazing and good compliments.

My special thanks go to the Olabisi Onabanjo University management. I will like to thank the Provost of the College of Engineering, Professor J. O Akinyemi; The head of the Department of Electrical & Electronic Engineering, Sectional heads, colleagues, and the university administrative staff who have been a pillar of support.

I am greatly indebted to my wife, Bolatiwa Adunni Olokede. As soon as I left Nigeria, you single handedly took up the challenges of taking over my responsibilities, first to you, my children, and finally, my parents. This I cannot thank you enough. I also want to thank my children: Jesutofunmi, Oreoluwa and Anjolaoluwa. I truly know how it feels to miss ones parents particularly at that formative years-Thank you! I specially want to thank my parents, parents-in-law, siblings and siblings-in-law. With attainment of this degree, I perceived I have adequately fulfils my mum’s dream toward my education. My gratitude also goes to all my cousins and friends in Nigeria and diaspora.

I am also indebted to these gentlemen who have lay aside all so as to have an oversight function over my life. I know you would not want your names to be mentioned. I thank you for your secrete hard work and anonymous labour over my life. It is my hearts cry that heaven will undertake on my behalf that I may not be a disappointment. My regards also goes to Ota class.

Further thanks to members of wireless and communication research group, both present and past. Thank you Yazeed Qasaymeh, Mohammed Ariff Othman, Ihsan Ahmad Zubir, Kang Chia Chao, Ubaid Ullah, Khairu Anuar, Ali Jaafa, Samiyeh Shaghaji, Umill Hasan, and Zulaimi Zahar. I also want to thank the Nigeria and Africa community (undergraduate, postgraduate, and post doctorate) in USM both past and present. I am equally indebted to members and families at my place of worship at Parit Buntar and Pinang.

Finally, I would like to thank the USM management, IPS, the Dean School of Electrical and Electronic Engineering, the Sectional heads, and the staff (academic and administrative), the Clinic staff, Student Affairs, and Transport division for their services that made my stay at USM a memorable one. On a particular note, I would like to acknowledge the USM Research University (RU) Grant under project number 1001/PELECT/854004.

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LIST OF SYMBOLS

ε_r	Dielectric Constant
ε_{eff}	Effective Dielectric Constant
Ω	Ohms (Impedance)
β	Phase Constant
γ	Propagation Constant
σ	Electrical Conductivity of Element
Δl	Equivalent Line of the Transmission
Δ	Width Correction Factor
λ_0	The Wavelength in Free Space
λ_g	The Guided Wavelength
Γ	Reflection Coefficient
η	The Radiation Efficiency
ω	Angular Resonant Frequency
B_m	The Susceptance of the Fringing Field Capacitance of the Microstrip
c	Speed of Light
C_0	Zero-Order Mode Capacitor
C_p	Pad/Parasitic Capacitor
C	Interdigital Capacitor
C_g	Gap Capacitor
C_h	Fringing Capacitor

C_l	Capacitance of the Microstrip Line
C_L	Overlapping Width of Interdigital Finger
C/N	Capacitance per Finger
E	Electrical Field
$E\theta$	Vertical Radiation Plane
$E\phi$	Horizontal Radiation Plane
f_o	Resonant Frequency
G_{rm}	Microstrip Radiation Conductance
G_S	Gain of Standard Antenna
G_T	Gain of Tested Antenna
h	Substrate Height
H	Magnetic Field
$H_0^{(2)}$	Henkel Function of the Second Kind
K	The Effective Propagation Constant of the Line
$K_0(.)$	Zero-Order Modified Bessel Function
k_o	The Free-Space Wave Number
$k_{x,}$	Wave Number in X Direction
k_y	Wave Number in Y Direction
k_z	Wave Number in Z Direction
J	Surface Current Density
L	Narrow Strip Shorted Inductor

L_0	Zero-Order Mode Inductor
L_r	Inductance of Dielectric Resonator
M	Proximity Coupling
N	Number of Fingers
P_{rad}	Radiated Power of Rectangular Antenna
P_S	Power Received by the Standard Antenna
P_T	Power Received by Tested Antenna
Q	Quality Factor
R_r	Resistive of the Resonator
S	Stub Extension
S_1	Stub Extension which to Half Wavelength
S_2	Stub Extension Equals to Quarter Wavelength
S_x	Elements Spacing in the X direction
Z_0	The Microstrip Characteristic Impedance
Z_i	Impedance of Infinite Width Ground
Z_{SC}	Impedance at Short Circuit End

LIST OF ABBREVIATIONS

ADS	Advanced Design System
AF	Array Factor
AUT	Antenna Under Test
BW	Bandwidth
BRAN	Broadband Radio Access Network
CST	Computer Simulation Technology
dB	Decibel
1-D	One Dimension
3-D	Three Dimensions
E-field	Electric Field
ETSI	European Telecommunications Standard Institute
HIPERLAN	High Performance LAN
HUMAN	High Speed Unlicensed MAN
GHz	Giga Hertz
GPS	Global Positioning System
GSM	Global System for Mobile Communication
IEEE	Institute of Electrical & Electronic Engineers
IDC	Interdigital Capacitor
LAN	Local Area Network
LE	Lumped Element
LP	Linearly Polarized
MAN	Metropolitan Area Network
MHz	Mega Hertz

MICs	Microwave Integrated Circuits
MIMCs	Monolithic Microwave Integrated Circuits
MIMO	Multiple In Multiple Out
MoD	Moment of Demand
MPA	Microstrip Patch Antenna
MPBG	Metallic Photonic Band Gap
MWS	Microwave Studio
PBG	Photonic Band Gap
Q-factor	Quality Factor
RF	Radio Frequency
RFICs	Radio Frequency Integrated Circuits
RFID	Radio Frequency Identification
SLL	Side Lobe Level
S-11	Scattering Parameter
SWR	Standing Wave ratio
TEM	Transverse Electromagnetic
TE	Transverse Electric
TM	Transverse Magnetic
U-NII	Unlicensed National Information Infrastructure
VSWR	Voltage Standing Wave Ratio
WiMAX	Worldwide Interoperability Microwave Access
WLAN	Wireless Local Area Network

REKABENTUK ANTENA PENYALUN ELEMEN KUASI—TERGUMPAL DENGAN SUAPAN GANDINGAN MAGNETIK

ABSTRAK

Kemajuan dalam sistem tanpa wayar dan permintaan yang meningkat dalam mobiliti tanpa wayar telah membolehkan penciptaan sistem tanpa wayar dapat digunakan. Menyedari hakikat itu, ringan, selesa, tidak terlalu menonjol, dan boleh disepadukan kedalam penggunaan harian, kini salah satu rekabentuk penting yang harus dipertimbangkan. Sistem-sistem komunikasi tanpa wayar mengandungi beberapa bahagian dimana antena padat adalah sub-bahagian yang penting. Walau bagaimanapun, banyak cabaran teknikal yang timbul dalam mereka bentuk antena yang teguh, padat dan cekap yang memberikan prestasi yang perlu untuk menyokong aplikasi-aplikasi terkini. Keterbatasan kepada panjang elektrik, rintangan radiasi yang rendah, faktor-Q yang tinggi, jalur lebar yang sempit, kesukaran penyuapan adalah antara pelbagai cabaran yang berkamungkinan dihadapi dalam merekabentuk antena kecil. Oleh itu, tujuan kajian ini adalah untuk membangunkan satu struktur antena alternatif yang memenuhi keperluan yang padat dari segi saiz antena, tanpa perlu mengkompromikan ciri-ciri radiasi antena. Tiga rekabentuk konfigurasi antena telah dibangunkan. Konfigurasi pertama adalah sebuah Struktur antena penyalun tunggal elemen kuasi-tergumpal yang ringkas dimana ia telah diujakan menggunakan sebuah kuar suapan sepaksi. Struktur antena tersebut telah difabrikasi di atas Duroid RO4003C dengan ketelusan daripada 3.38 dan ketebalan 0.813 mm. Saiz penyalun adalah 5.8×5.6 mm^2 dengan ketebalan konduktor 0.035 mm. Simulasi, fabrikasi dan pengukuran telah dilakukan untuk menyiasat ciri-ciri prestasi penyalun untuk mengesahkan potensi yang wujud pada penyalun yang dicadangkan sebagai calon antena. Persamaan dan rekabentuk radiasi telah dibentangkan. Berdasarkan pemerhatian dari konfigurasi yang pertama, sebuah penyalun 6-siri elemen kuasi-tergumpal dan sebuah susunan satah segi empat tepat telah direkabentuk, difabrikasi dan diukur. Konfigurasi seterusnya di uja dengan kuar suapan sepaksi, manakala konfigurasi sebelumnya disuap oleh garis mikrostrip dan teruja dengan kuar suapan sepaksi. Pemodelan ketiga-tiga konfigurasi yang telah dibangunkan dibuat menggunakan Agilent Design Software (ADS). Litar-litar setara dan keputusan-keputusan pemodelan telah dilaporkan. Keutuhan dan kecekapan antena yang telah dibangunkan disiasat dengan menjalankan kajian analisis perbandingan dengan antena satah yang berbeza jenis dan struktur. Penemuan-penemuan menunjukkan bahawa keputusan yang baik dimana keputusan simulasi adalah sama dengan keputusan eksperimen. Elemen antena tunggal yang dicadangkan telah menunjukkan keupayaan pengurangan saiz sebanyak 86.55 % berbanding dengan antena tampal kuar suapan sepaksi/slot, dan 84.96% berbanding dengan antena wayar panjang yang konvensional. Tatasusun satah sesiri dan segi empat tepat menggambarkan corak yang sama di mana satah segi empat sama yang dicadangkan mempunyai pengurangan saiz sebanyak 74.74% berbanding tampalan. Tatasusun sesiri menunjukkan pengurangan 85.5 % berbanding tampalan, 80.49 % antena slot, dan 61.29 % berbanding tatasusun sesiri antena wayar. Tambahan pula, elemen tunggal yang dicadangkan telah mencapai gandaan sebanyak 9.38 dBi terhadap antena-antena tampalan/wayar yang telah di optimumkan secara berbeza, dan gandaan untuk 12.17 dBi untuk tatasusun sesiri terhadap 11.04 dBi, dan gandaan untuk 23.06 dBi untuk tatasusun bersatah terhadap 18.17 dBi untuk antena-antena tampalan/wayar tatasusunan siri yang telah dikonfigurasi dengan berbeza dan tampalan antena satah segi empat. Kesimpulannya, antena yang dicadangkan mempunyai kelebihan lebar jalur yang lebih baik dengan nilai 340 MHz, 242 MHz, dan 310 MHz. Selain daripada kelebihan yang disebutkan di atas, antena yang dicadangkan mempunyai kelebihan saiz kecil yang ketara dalam memastikan kepadatan yang diperlukan.

DESIGN OF A QUASI-LUMPED ELEMENT RESONATOR ANTENNA WITH MAGNETIC COUPLING FEEDING

ABSTRACT

Advancement in wireless systems and subsequent increasing demand in wireless mobility has enabled the invention of the wearable wireless systems. Realizing this fact, lightweight, conformable, unobtrusive, and ubiquitous equipment, which can be integrated into everyday use, are now crucial design considerations. These wireless communication systems contain several parts in which compact antennas are an essential subpart. However, many technical challenges arise in designing robust, compact and efficient antennas that deliver the necessary performance to support the emerging applications. Limitations due to electrical length, low radiative resistance, high Q-factor, narrow bandwidth, feeding difficulties are among the numerous challenges confronting the feasibility of designing small antennas. Therefore, the intent of this work is to develop an alternative antenna structure that meets the compact requirements in terms of size, without compromising the antenna radiation characteristics. Three antenna designs configurations are developed. The first design is a simple single quasi-lumped element resonator antenna arrangement which was excited by a coaxial feed probe. The antenna structure was photo-edged on a Duroid RO4003C with a permittivity of 3.38 and thickness of 0.813 mm. The size of the resonator is 5.8×5.6 mm^2 with conductor thickness of 0.035 mm. The simulation, fabrication, and measurement were conducted to ascertain its performance characteristics thereby validating the inherent potential of the proposed resonator as an antenna candidate. The design and radiation equations were presented. Based on the performance of the first configuration, a 6-element series array quasi-lumped element resonator antenna and the rectangular planar array were designed, fabricated and measured. The latter configuration was excited by the coaxial feed probe, whereas the former was fed by a microstrip-line and excited with a coaxial feed probe. The modelling of the three developed configurations was done by using Agilent Design System (ADS). The robustness and effectiveness of the developed antennas

were investigated by conducting a comparative analysis study of different metal antenna types and structures. Findings indicate that all the experimental results are in good agreement with the simulated results. The proposed single element antenna demonstrates a size reduction capability of 86.55 %, as compared to a coaxial-fed patch/slot antenna, and 84.96 % as compared with conventional long wire antenna. The series and rectangular planar array portray similar trend in which the proposed rectangular planar array has a size reduction of 74.74 % over the patch. The series array demonstrates a reduction capability of 85.15 % over the patch, 80.49 % over the slot, and 61.29 % over the series array wire antennas. Additionally, the proposed antenna has a better gain of 9.38 dBi for single element as against differently optimized single element patch/wire antennas' gain, and a gain of 12.17 dBi for series array as compared to 11.04 dBi, and 23.06 dBi for planar array as against 18.17 dBi for differently configured series array patch/wire antennas, and the rectangular planar patch antennas respectively. In conclusion, the proposed antenna has superior advantages of improved measured bandwidths of 340 MHz, 242 MHz, and 310 MHz respectively. Besides the aforementioned advantages, the proposed antenna has significant small size advantage which ensures its required compactness.

CHAPTER 1

INTRODUCTION

1.1 Background

At the close of the eighteen century, the numbers of antenna in the world could be numbered; and toward the tail end of the Second World War, the numbers have increased significantly that antenna were gradually becoming ubiquitous. At the turn of the century, a full size antenna was often too costly to erect and by necessity, one solution to this problem was to construct top-loaded antennas using supporting towers, thereby reducing the height of the antenna. Other types of reduced height and constrained size antennas were devised during the World Wars to satisfy various operational requirements at higher frequencies (Fujimoto, 1987).

The aftermath of the World War II launched a new era in antenna due to the introduction of modern technology and new elements such as waveguides apertures, horns, and reflector with detail list in (Waterhouse, 2007). Inventions of microwave sources such as the klystron and magnetron with frequencies well above 2 GHz were contributing factor. In addition, advances in computer architecture and technology during the 1960s through to 1990s have had major impact on the advances of modern antenna technology (Balanis, 1997). It has contributed in no measure to this rapid reduction in its physical size due largely to the development of integrated circuit.

By the end of the 20^{th} century, the advent of GSM technology introduced another dimension to the dire need for antenna miniaturization. Of course, this is due largely to ever increasing demand for mobile phones, GPS systems, handheld portable wireless equipment for internet, short- and long-range communication devices, RFID applications etc. More importantly, the need for small antennas is gradually becoming crucial and pressing, partly because of insufficient space to fit conventional antennas as often times, the platform onto which the antenna is to be mounted or interfaced, is itself physically small. It is imperative to address the issue of compact antennas with recourse to the effect of small platforms.

Take for instance, a conventional microstrip patch antenna have been unsuitable because of its size, particularly for mobile communication applications. The frequencies of less than 2 GHz require a conventional microstrip patch too large to be readily installed on typical dimension of a mobile communication handset (Waterhouse et al., 1998; Vendelin, 1990). Therefore, it then incumbent on system designers to note that these applications and continued growth of wireless devices will continue to challenge the community to create smaller and more multifunctional antennas (Volakis, 2010).

However, the reduction in antenna size presents problem to the system designers due to the performance limitations in antenna bandwidth and radiation efficiency. These shortfalls have to be absorbed into the overall system performance of the equipment, which could results in very poor reception. Though, a reduction in overall efficiency may still be achieved, but the failure to incorporate matching techniques could lead to even worse system deficiency. Much more, the trade-off between antenna size and performance is in general difficult to predict for practical situations, particularly where matching units are involved and evaluations tends to be experimental. Because of these, designers in many sector of the market are now demanding more precision in small antenna design, so that any performance penalties incurred can be minimized.

In this work therefore, a quasi lumped resonator antenna is presented as a better alternative to achieving compactness with sufficient radiation characteristics. It can be widely employed in Microwave Integrated Circuits (MICs) and Monolithic Microwave Integrated Circuits (MIMCs) for wireless technology applications, due to its significant size reduction, intrinsic low cost, low mass, low volume, light weight, construction simplicity, relatively high Q-factor and repeatability (Caratelli, 2003). It offers a good system performance and considerable size reduction when compared with conventional Microstrip patch antenna, some selected but common performance enhancement microstrip patch antennas, Slot antenna, Vivaldi, the standard wire antenna approach, and, in particular, also to the many available differently loaded long wire antenna approaches, which are also optimized for maximal radiation efficiency and directivity, such as, the capacitive loaded long wire dipole antenna, the planar H-shaped elements loaded transmission-line design at the same resonant frequency, and yet do not compromise the overall efficiency.

1.2 Problem Statement

Since the advent of microstrip patch antennas in 1970s, they are becoming increasingly popular and useful. However, they suffer severe operational disadvantages such as low efficiency, low power, high Q-factor, poor polarization purity, poor scan performance, spurious feed radiation and very narrow frequency bandwidth (Balanis, 2007; Medeiros et al, 2007). Many compact antennas including dipole antenna, monopole antenna, and rectangular planar antenna configurations have been reported (Deepu et al, 2007; Lee & Sun, 2008; Li & Gan, 2006; Mishra Liu & Liu, 2006; Tilanthe et al, 2011a/b). These compact antennas suffer severe limitations in terms of size due to their electrical length limitation. Take for instance, a conventional half dipole wire antenna for 5.8 GHz cannot be less than 26.86 mm in dimension, and 14 mm for planar half dipole wire antenna when photo etched on R4003C Duroid laminate microwave board.

They also suffer severe limitations in terms of bandwidth and gain most especially as a result of miniaturization. When the size of antenna is reduced, the antenna do not only provides low value of directivity as a result of reduced radiative resistance that lead to the problem of decreased radiative efficiency as the ratio of the antenna conductor to the radiated power decreased with increase in frequency (Harrington, 1961 & 2001), but also demonstrates a rapid increase of Q-factor with attendant decrease in bandwidth. By implication, the reduced size of the antenna becomes sensitive to excitations, positions, and also to the associated tolerances. Therefore, small antennas are confronted with feeding difficulty often due to the reduced size of the antenna with respect to the antenna itself. Therefore, to overcome these challenges, a quasi-lumped element resonator antenna operating at 5.8 GHz frequency is presented.

1.3 Aims and Objectives

The main aim of this research work is to design an alternative antenna solution in the IEEE 802.11a Upper U-II/ISM band (5.75-5.875), ETSI-BRAN HIPERLAN/2, and IEEE 802.16b Upper U-II/ISM band (5.725-5.850) bearing in mind the mobility and portability potential of the proposed antenna. The intent therefore, is to devise alternative antenna design, different from the existing conventional antennas that will meet the set goals of reasonable impedance bandwidth, intrinsic low cost, construction simplicity, low mass, light weight, relatively high Q-factor, repeatability and most importantly with significant size reduction. To accomplish this aim therefore, these objectives listed below have to be meticulously carried out:

i. To develop an alternative antenna design solution whose resonant frequency does not depend on its electrical length but rather on some lumped element components (such as capacitor and inductor) even though it is a resonant antenna. Therefore, a quasi-lumped element resonator antenna is introduced with potential significant size reduction capability.

ii. To enhance the directive (gain) characteristics of the proposed antenna so as to satisfy the demand of long distance communication via the instrumentality of the array configurations, while maintaining it's simple and compact structure.

iii. To design, fabricate and measure some conventional and available performance enhancement antennas with the view to compare their performances with the proposed antenna.

iv. To model the proposed antennas (all the three presented designs), compare the model results with the simulated and measured results, and finally, validates these modelled results with the existing theoretical background. Doing this will further explore the inherent peculiarities of the proposed structure.

1.4 Scope and Limitations of Research

The scope of this work is to design a coaxial-fed quasi-lumped element resonator antenna with compact capability as a goal. All the designs are excited by a coaxial feed probe, and the entire designs are photo etched on the microwave substrate from Roger Corporation RC4003C with relative permittivity of 3.38, thickness of 0.813 mm, and loss tangent of 0.0027. Computer Simulation Technology CST microwave office utilizing the Moment of Demand (MoD) approach was used throughout the project for full wave analysis so as to fully understand the performance characteristics of the proposed antenna.

Designs specifications were set, and necessary designs equations to achieve the specifications were investigated. Different design configurations of the proposed antenna were designed with respects to these specifications. Similar arrangements were also done for selected but different types of planar metal antenna configurations, and their performance were compared. This is done to demonstrate the proposed antenna's specific advantages.

Thereafter, the simulation was done using CST microwave studio. The return loss, bandwidth, radiation pattern, and the gain characteristic of the antenna can be determined prior to fabrication. Subsequently, modelling of the single quasi-lumped resonator antenna with the coaxial probe feed, six-element microstrip-fed coaxial excited quasi-lumped element resonator antenna array, and finally, 9×10 proximity coupled coaxial excited planar rectangular antenna were done. These models were done by calculating the lumped element equivalents of their respective feeds and the proposed resonator.

Finally, the antenna was fabricated and measured. The simulated results were then compared with the measurement results to ascertain the degree of agreement. These results were analyzed, discussed, and conclusions were drawn based on the observations. The proposed resonator could further be reduced but there is impending etching limitation. The available machine can only etch to a minimum trace and gap of about 0.3 mm.

1.5 Thesis Contributions

The contribution of this work is to device an alternative compact antenna element suitable for wireless communication applications. To this end, a novel quasi-lumped element resonator antenna structure is introduced. Because it is a lumped element, the antenna footprint is reduced significantly, and hence, its real estate. Since the proposed antenna is a novel structure, though a type of microstrip patch antenna (MPA)

i. A new antenna structure was introduced. The proposed antenna, a quasi-lumped element resonator antenna has capacity for reduced footprint as well as the estate area.

ii. Modelling of the proposed antenna was done for single element, series array and the planar array configurations.

iii. The existing far field radiation pattern equations were modified and adapted for the proposed single quasi-lumped resonator antenna. The electric field intensity of the element, the far field radiation pattern, and the array factor of the proximity coupled rectangular planar array were similarly adapted.

1.6 Thesis Outline

The organization of the thesis write up has been divided into five Chapters. Chapter 1 gives a concise introduction of the basic concepts and motives behind the work. It also describes the problem statements, the objectives as well as the scope of the study.

Chapter 2 provides the detailed background and thorough review of the existing but relevant literatures. The Chapter focuses more on lumped element capacity for small antennas miniaturization techniques and applications, which are germane to the objectives of the study. Furthermore, the theoretical frameworks and design concept as a foundation for experimental procedures were reported. The concept of quasi-lumped element as a single element resonator (consisting of microstrip lines and short Sections as the basic building blocks of the proposed resonator), the array configuration geometry and their performance profile are explained in details.

Chapter 3 explains in details and convincingly the experimental procedures and methodology carried out to achieve the set objectives. These theoretical and experimental procedures including the simulation procedure which was done using CST software, fabrication process to produce the quasi-lumped element resonator antenna, coupling considerations, and modelling procedures of the proposed antenna configurations were presented.

In Chapter 4, simulation, measurement, and modelled results were carried out, thoroughly analyzed and reported. The modelled results were also validated. Much more, the simulation results of the S-parameter for all the configurations including their radiation patterns and gains were clearly stated. The performance profile comparison between the proposed antenna and some selected antennas was investigated and results documented appropriately.

Finally, Chapter 5 summarizes the results of these deigns in line with the set aims and objectives. Contributions of the project were itemized. Suggestions and recommendation for future work were also presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Theoretical Background

Recently, applications requiring physically small size are ubiquitous. Because of the reduced size of the wireless devices, antennas are required to be physically and in most cases also electrically small (Wansch, 2002). Often times, conventional microstrip patch antennas have been unsuitable because of the size requirement, particularly for mobile communication applications. The frequencies of less than 2 GHz require conventional microstrip patches too large to be readily installed on typical dimensions of a mobile communication handset (Vendelin et al, 2005). The increasing needs for small antennas are due to the more and pressing demands for low manufacturing cost, portability, strait space requirement, and light weight for easy mobility and wearable (Hui & Luk, 2005). Therefore as a result of compactness, the small antennas are feasible to be integrated with monolithic integrated circuit (Kumar & Ray, 2003).

Also, MIMO technology has attracted attention in wireless communications in the recent times, because of its significant increase in data throughput capability and link range efficiency without additional bandwidth or increased transmit power. While coding and signal processing are key elements to successful implementing a MIMO system, the propagation channel and antenna design represent major parameters that ultimately impact the system performance. To create a MIMO antenna system on a wireless handy device, only small space is allocated, and therefore, small and compact antenna is adequate and preferable. Besides, the efficiency of the antenna should be high enough to ensure long battery life as most of the terminals are battery-driven (Waldschmidt et al, 2005).

For the next generation air defense systems, radar system need to be improved to support new Air Defense System which include high mobility, transportability, remote operation in strait, intense and dense terrain, high degree identification precision and increased sensitivity to detect smaller targets at longer ranges (Harlan Jr. et al, 2006).

Therefore, small and compact antenna is an essential and critical to fulfilling these requirements. On the average, the specific advantages of using small size array antenna element, is partly to contribute to the reduction on antenna weight and also, lead to the lighter rotators for the mechanical scanning. Much more is the ease of mobility.

A small and light weight antenna will be a necessity to support high mobility requirement for most wireless applications. More importantly, the development of antenna for wireless communication requires an antenna with more than one operating bands. New and emerging converged technologies in communication applications normally associates themselves with increasing data rates and wide frequency band required for multiple integrated services such as direct digital broadcast, video–conferencing, indoor wireless as well as new wireless standard demand (Petosa et al, 1998). In recent times, it is not uncommon to use a single antenna to provide full coverage over the entire frequency range.

2.2 Review of Existing Works on Lumped Element

2.2.1 Overview of the Lumped Element

Prior to 1960s, lumped elements have been in existence and subsequently become popular because of their capacity for size reduction, distinct benefits in terms of bandwidth as well as electrical performance. Lumped element circuit can be categorized into passive and control circuits. The passive lumped element circuit can further be subdivided into ceramic lumped element or superconducting lumped element microwave circuits. The lumped element is ceramic if thick film printed inductors and discrete capacitors are used. Otherwise, it is superconducting when high temperature superconductor (HTS) substrates are used instead of the Duroid microwave substrate (Bahl, 2003).

Because of their capacity for size reduction and also to provide distinct benefit of reasonable bandwidth, they have found a wide application in filter designs, and more recently in antenna designs. The application of the concept was first introduced in 1965 by Vincent (Vincent, 1965) for possible use in microwave integrated circuits (MICs). In 1967, Daly et al reported the lumped elements in microwave integrated circuits (Daly et al, 1967). By 1970, Alley reported the interdigital capacitor and their applications to lumped element microwave integrated circuits where he identified specific advantages of lumped element circuits over the microstrip circuits even though its fabrication technique follows the same processing steps required in the fabrication of conventional thin-film microstrip circuits (Alley, 1970). In the same year, Caulton et al (1070) published the status of lumped elements in microwave integrated circuits-present and future. Between 1960s through to 1970s more than seven published works were reported describing the design, measurement, and applications of lumped elements with intention to primarily reduce the size of MICs at the lower end of the microwave frequency band where microstrip circuits proved to be too large in size to be readily adapted for MICs.

Subsequently, between 1970s through to 1980s witnessed tremendous progress using lumped element for MICs at operating frequencies as high as 12 GHz (Zhao et al, 1997; Niknejad & Meyer, 1998; Park & Allen, 1999), and later became an integral part of microwave circuit design at the advent of Monolithic Microwave Integrated circuits (MIMICs) in 1976 (Chang, 1989; Caulton & Daly, 1968; Wheeler, 1928; Pettenpaul et al, 1988; Greenhouse, 1974; Camp Jr. et al, 1983). In 1999, Wang & Lancaster published aperture coupled thin-film superconductivity meander antenna (Wang & Lancaster, 1999). By the year 2005, Jeong et al reported the design of a corner-truncated square-spiral microstrip patch antenna (MPA) in the 5 GHz band using lumped element circuits and excited by coaxial feed probe (Jeong et al, 2005). Ever since then, different research works are ongoing with different novel antenna solutions using the instrumentality of lumped element circuits with a view to underscore its small size premium.

2.2.2 Features of the Lumped Element

A lumped element is usually defined as a passive component whose size across any dimension is much smaller than the operating wavelength in which they operate (Bahl, 2003). It is therefore not uncommon to see the lumped element circuits with no appreciable phase shift between the input and output terminals. Hence, common lumped element components primarily includes: capacitors, inductors and finally, resistors. In some cases, lumped inductor transformer, as well as balun is freely used in lumped element circuits. Keeping the maximum dimension less than λ/20 is a good approximation (where λ is the guided wavelength) and to that extent, makes lumped element an attractive alternative technology in wireless communications, and hence offers many appalling features as listed below.

i. They have the advantage of smaller size, lower mass/volume, lower cost, and wider bandwidth characteristics

ii. They offer impedance transformation of the order of 20:1 with ease using lumped element approach. It is as a result of this that makes high-power devices with very low input and output impedance values be readily matched to 50 Ω possible using large impedance transformers via lumped elements.

iii. Lower mutual coupling between adjacent lumped element circuits due to low coupling effect particularly when compared with microstrip circuits.

iv. Lower amplitude and phase variations due to smaller phase delays. This feature helps further in realizing high efficient compact circuits.

v. At RF and the low end of the microwave band, the chip size becomes significantly smaller at the instance of the use of lumped element circuits without affecting the RF performance. This inadvertently increases the number of chips per wafer, gives improved visual and RF yields, and consequently reduce chip costs drastically.

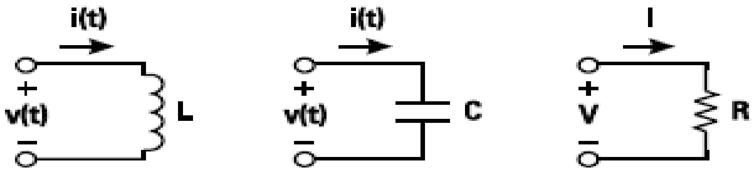
vi. Several design techniques used in circuits at lower RF frequencies, which were aforetime not feasible or practical at microwave frequencies using microstrip, coaxial, or waveguide transmission media, can now be successfully applied up to X-band frequencies.

vii. Lumped inductors with much lower parasitic capacitance will result in wider bandwidth circuits. This can be implemented to tune out the active device capacitance, using an inductance with the minimum possible parasitic capacitance.

2.2.3 Basic Designs of the Lumped Element

2.2.3.1 Basic Circuit Components

In Section 2.2.2, the primary components of lumped element circuit were identified as capacitor, inductor, and resistors. It will therefore be correct to review the basic mathematical relationship between the terminal voltage and current across the circuit elements so as to form the background for this study. Consider that these elements (Inductor, L; Capacitor, C; and Resistor, R) as shown in Figure 2.1 are ideal (pure and linear).



(a) (b) (c)

Figure 2.1: Two Terminal Voltage/Current Representation of Lumped Circuit Elements. (a) Inductor, (b) Capacitor, (c) Resistors (Bahl, 2003)

Figure 2.1(a) represents an ideal inductor of inductance *L*, which stores or releases magnetic energy W_m, and does not store electric energy. It also does not dissipate any power and the phase of the time-varying electric current i(*t*) lags the phase of the voltage *v*(*t*) across its terminals as stated in Equation (2.1)

$$i(t) = \frac{1}{L}\int v(t)d \qquad (2.1)$$

where

$v(t) = L\frac{di(t)}{dt}$, $w_m = \frac{1}{2}Li_0^2$ and i_0 is the rms value of the current.

Figure 2.1(b) is an ideal capacitor of capacitance *C*. The stored or released energy is only of electric type W_e, and such components do not dissipate any power. In an ideal capacitor, the phase of the electric current $i(t)$ leads the phase of the voltage $v(t)$ and the relationships between *v* and *i* are expressed as stated in Equation (2.2)

$$i(t) = C\frac{dv(t)}{dt} \tag{2.2}$$

where

$v(t) = \frac{1}{C}\int i(t)d$, $W_e = \frac{1}{2}Cv_0^2$ and, v_0 is the rms value of the voltage.

In a linear resistor (a lossy component whose dimensions are less than the operating wavelength), the voltage and current across its terminal are in phase and hence, the incident power is completely dissipated.

2.2.3.2 Lumped Element Realization

At RF and microwave frequencies, lumped elements are designed based on small Sections of TEM lines such as microstrip lines. A lumped capacitor may be realized by using an open-circuited ($Z_L = \infty$) microstrip Section, whereas a lumped inductor is realizable using a short-circuited ($Z_L = 0$) microstrip Section. Thus a small-length short-circuited transmission line behaves as an inductor in series with a resistor *R* (Bahl, 2003). Though, the short-circuited transmission line behaves as an inductor when the conductors have low resistance. It however behaves otherwise particularly when a Section of good conductor is replaced with thin lossy conductor such as NiCr (gold). In such cases, the resistive part becomes dominant and the microstrip Section behaves like a resistor with negligible parasitic inductive and capacitive reactances.

2.2.4 Equivalent Circuit Representation of the Lumped Element

In early 1943, Terman propose an expression for the inductance of a thin metallic straight line using analytical semi-empirical equations. This expression was later improved by Caulton et al (1968), who added the effect of metallization thickness. Wheeler (Wheeler, 1928) presented an approximate formula for the inductance of a circular spiral inductor with reasonably good accuracy at lower microwave frequencies. This formula has been extensively used in the design of microwave lumped circuits and are as stated in Section 3.3.1.

Subsequently, Grover (1962) investigated inductance calculations for several geometries. In most cases, it has been found out that the theoretical modelling of microstrip inductors for MICs has usually been based on two methods. The first method is based on the lumped-element approach, whereas the second is based on the coupled-line approach. The lumped-element approach uses formulas for free-space inductance with ground plane effects. These frequency-independent formulas are useful only when the total length of the inductor is a small fraction of the operating wavelength and when inter-turn capacitance can be ignored. In the coupled-line approach, an inductor is analyzed using multi-conductor coupled microstrip lines. The later technique predicts performance reasonable well for coupled structure up to about 18 GHz (Bahl & Bhartia, 2003).

The need for these models, and by implication their efficiency became imperatives as an ideal lumped element is not realizable even at lower microwave frequencies because of the associated parasitic reactances due to fringing fields (Bahl, 2003). More so is at RF and microwave frequencies, where each component has associated electric and magnetic fields and finite dissipative loss. Thus, such components tend to store or release electric and magnetic energies across them and their resistance accounts for the dissipated power. In most cases, the relative values of the capacitance, inductance and resistance components in these elements depend on the intended use of the lumped element. To describe their electrical behavior, equivalent circuit models for such components are commonly used. By definition therefore, lumped element equivalent circuit models consist of basic circuit elements (*L*, *C,* or *R*) with the associated parasitics.

Accurate computer aided design of MICs and MMICs requires a complete and accurate characterization of these components. This requires comprehensive models including the effect of ground plane, fringing fields, proximity effects, substrate material and thickness, conductor thickness, and associated mounting techniques and applications. Thus, an equivalent circuit representation of a lumped element with its parasitics and their frequency-dependent characteristics is essential for accurate element modelling (Bahl & Bhartia, 2003). It is on the basis of these facts that the equivalent circuits of the resonator, the equivalent circuit of the three presented antenna configurations, and as well as their respective modelling was done and consequently presented. The equivalent circuit's models of all the designs consist of the circuit elements necessary to fully describe their responses, including resonances, if any. The models employed also include: analytical numerical method using requisite design equations, the Moment of Demand (MoD) based electromagnetic simulation using CST, and measurement based methods.

The current distribution within the cross-Section of each finger, an approximation for which is stated in Equation (2.3).

$$\sigma(x) = \frac{2I}{\pi w\sqrt{1-\left(\frac{2x}{w}\right)^2}} + \frac{2I^{'}}{\pi w\sqrt{1-\left(\frac{2x}{w}\right)^2}}\frac{2x}{w} \qquad -l/2 \le x \le l/2$$

(2.3)

where *x* is measured transversely from the Centre of a strip. The first term is implied by the conformal mapping reported by Huang (Huang et al, 1999), and I can be found similarly. I' can be evaluated in a second iteration by requiring that the flux through the strips be zero. In (Itoh & Menzel, 1981), the authors presented a full-wave analysis of the open printed circuit structures such as those encountered in microstrip antennas as an eigenvalue problem with complex eigenvalue (resonant frequency), and subsequently derived the far field radiation patterns of the structure.

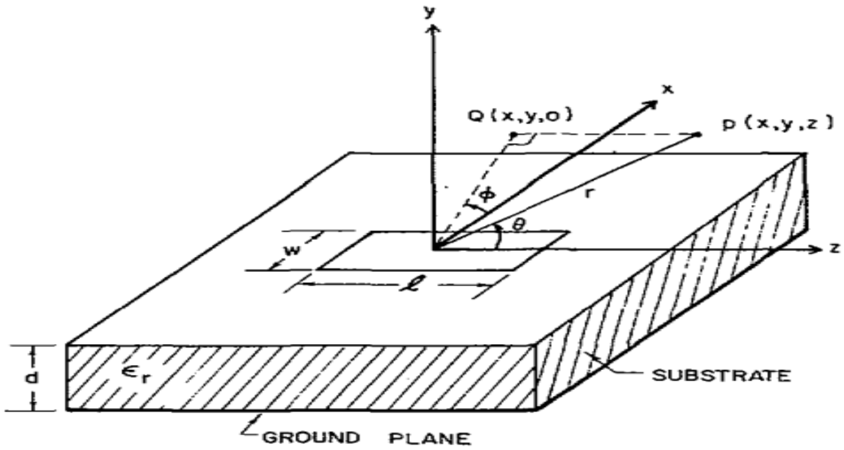


Figure 2.2: Open Microstrip Resonant Structure. (Itoh & Menzel, 1981)

In their work, Equation describing the surface wave density across the edges of the structure bearing in mind the correct singularities of the current distribution at the edges are incorporated as stated in Equations (2.4) and (2.5) with their parameters defined as shown in Figure 2.2. The current becomes singular at the edges parallel to the current and zero at the edges normal to it.

$$J_{zm}(x,z) = \frac{Cos\left[(r-1)\pi\frac{2x}{w}\right]Cos\left[(2s-1)\pi\frac{z}{l}\right]}{\sqrt{\left(\frac{w}{2}\right)^2 - x^2}\sqrt{\left(\frac{l}{2}\right)^2 - z^2}} \tag{2.4}$$

$$J_{xm}(x,z) = \frac{Sin\left[2r\pi\frac{x}{w}\right]Sin\left[(2s-1)\pi\frac{z}{l}\right]}{\sqrt{\left(\frac{w}{2}\right)^2 - x^2}\sqrt{\left(\frac{l}{2}\right)^2 - z^2}} \tag{2.5}$$

2.2.5 Application of the Lumped Element

Lumped elements have found ready and wide applications in RF and microwave circuits including but not limited to couplers, filters, power dividers/combiners, impedance transformers, baluns, control circuits, mixers, multipliers, oscillators, and finally, amplifiers (Bahl & Bhartia, 2003). In reality,

Table 2.1: Summary of Existing Works on Lumped Element Antennas

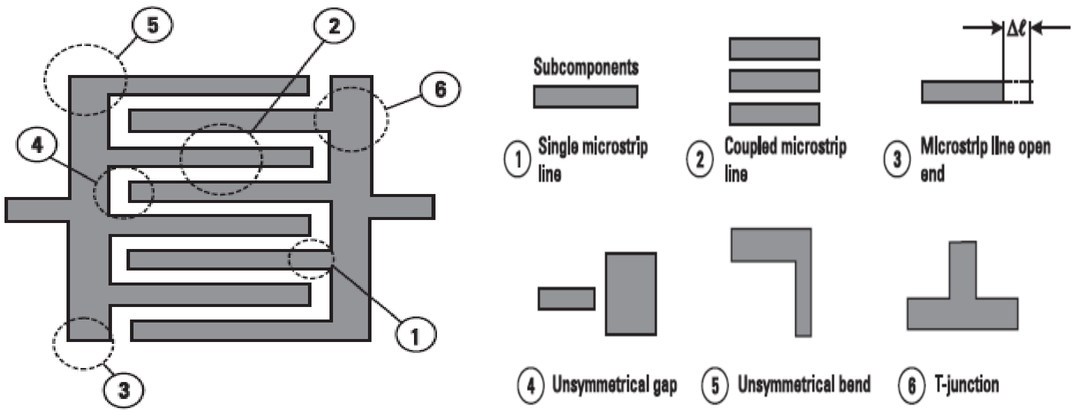
Nos.	Published Work	Bandwidth (MHz)	Frequency Band (GHz)	Permittivity (ε_r)	Substrate Thickness (mm)	Size (mm)	VSWR	Gain (dBi)	Feeding Method
1.	Choi et.al, 2013	85 725	2.45 5.75	4.55	1.6	10×5	3:1	4.07 2.55	Not Reported
2.	Hosono et.al, 2012	Not Reported	1.36	4.55	1.6	25×25	1.5:1	Not Reported	Not Reported
3.	Jeong et.al, 2006	200	5.8	4.55	1.6	17×17	1.5:1	7.3	Coaxial Feed
4.	Lin et.al, 2005	Not Reported	Not Reported	4.55	1.6	20×50	1.9:1	8-10	Not Reported
5.	Park et al, 2013	20	1.6	4.55	1.6	12×11	Not Reported	7.64	Not Reported
6.	Wang & Lancaster, 1999	45	Not Reported	10.8	1.27	45×100	Not Reported	Not Reported	Not Reported
7.	Rashed & Chen-To, 1991	Not Reported	5.55	Not Reported	Not Reported	45×150	Not Reported	Not Reported	Coaxial Feed
8.	Kan & Waterhouse 2002	38	1.98	1.07	10	17×25	Not Reported	Not Reported	Coaxial Feed

Lumped element-based circuit design using inductors, capacitors, and resistors is a key technique for reducing MMIC chip area, resulting in more chips per wafer and leading to lower costs. They therefore, have significant benefits over MICs in terms of smaller size, lighter weight, improved performance, higher reliability, and, most importantly, lower cost in high-volume applications. Most importantly, application of spiral geometry either circular or rectangular is recently not uncommon in printed antennas for wireless communication. Such antenna structures can result in a small, low-profile, conformal antenna as demonstrated by (Kan & Waterhouse, 2002) and much more, as demonstrated by other authors summarized in Table 2.1 Lumped element antennas are generally very suitable for handsets for mobile communication due to their ultra-small size compared to patch antennas (Bahl, 2003).

2.3 Review of Quasi-Lumped Element Resonator Characterization

Basically, the quasi-lumped element resonator consists of an interdigital capacitor in parallel with a strip inductor where the inductor is the centre finger shorted across the capacitor. Characterization and analyses of interdigital capacitors have been reported by Bahl, and Bhartia (Bahl & Bhartia, 1988); Gupta et al., (Gupta et al., 1996); Hobdell, (Hobdell, 1979); Alley, (Alley, 1970); Sadhir et al (Sadhir et al, 1994); Pettenpaul et al., (Pettenpaul et al., 1998); Esfandiari et al. (Esfandiari et al, 1983); and Joshi et al (Joshi et al, 1988).

The analyses were rather based on lossless microstrip coupled lines (Alley, 1970) and lossy coupled microstrip lines (Hobdell, 1979). Instead, a more accurate characterization of these capacitors can be performed if the capacitor geometry is divided into basic microstrip Sections and subcomponents as demonstrated in Figure 2.3. This model could therefore be said to provide better accuracy than the previously reported analyses. Nonetheless, this method can at best be regarded as an approximate solution rather than an exact or explicit. This is due to several assumptions in the grouping of sub-Sections and as such, could not account for interaction effects between the basic microstrip Sections.



(a) (b)

Figure 2.3: Lumped Structure. (a) Interdigital Capacitor, (b) Subcomponents (Bahl, 2003)

Therefore, the subcomponents of the geometry of the capacitor are henceforth studied in details so as to put together their functionality, peculiarities, and limitations. When this is done, a better characterization, and hence appropriate analysis can be done. To this end, the subsequent Sections will present detailed but concise review of the geometry subcomponents with a view to identify their peculiarities.

2.3.1 The Q-factor of Quasi-Lumped Element Resonator

The quality factor (Q-factor) is the figure of merit for assessing the performance of a resonator. The Q-factor for the interdigital capacitors is usually higher than that of overlay capacitors (which are often larger in size). Equation (2.3) below is a closed form equation for calculating Q-factor of an interdigital capacitor structure (Bahl, 2003).

$$Q_c = \frac{3wN}{4\omega lCR_s} \tag{2.3}$$

where C is the interdigital capacitance, R_s is the sheet resistance of plated gold conductor greater than four skin depth which can be determined by the equations stated in (2.4-5) below, and are, as reported by Bahl (Bahl, 2003). ω is the resonant frequency, N is the number of fingers, l and w are width and length of the structure respectively.

$$R_S = \frac{4}{\sigma w}\left[0.25\frac{w}{\delta} + 0.2654\right] \tag{2.4}$$

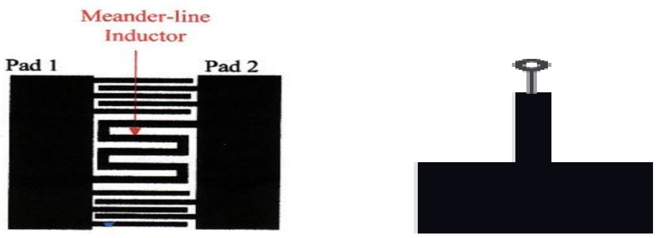
$$\delta = \frac{4}{\sqrt{\pi\sigma f \mu_0}} \tag{2.5}$$

where δ is the skin depth, σ and μ are the metal conductivity and permittivity of the material respectively.

2.4. Compact Microstrip Resonators

2.4.1 Lumped-Element or Quasi-Lumped-Element Resonators

Lumped or Quasi-Lumped-Element Resonators are formed by combination of the lumped or quasi-lumped components such as lumped inductors and capacitors as shown in Figure 2.4. Usually, they will resonate at $\omega_0 = 1/(\sqrt{LC})$. They may also resonate at some higher frequencies, at which their sizes are no longer much smaller than a wavelength, and by definition, are no longer lumped or quasi-lumped elements (Hong & Lancaster, 2001).



(a) (b)

Figure 2.4: Lumped-Element Resonator. (a) Lumped, (b) Quasi-Lumped (Hong & Lancaster, 2001)

2.4.2 Interdigital Capacitor Resonator

Interdigital finger capacitor (IDC) shown in Figure 2.5 is a multi-finger periodic structure that relies on the capacitance that occurs across the narrow gap between the parallel conducting fingers on a substrate (Bahl, 2003). They relies on the fringing capacitance between the long common edge areas of the metal fingers which are separated by very small spacing depending on the minimum gap permitted by the foundry. The fringing capacitance is fairly low, and is usually up to about 1 pF. The finger width *w* must equal the space *s* to achieve maximum capacitance density, and the substrate thickness *h* should be much larger than the finger width. Generally, they are suitable for applications where low values of capacitance (less than 1 pF) are required.

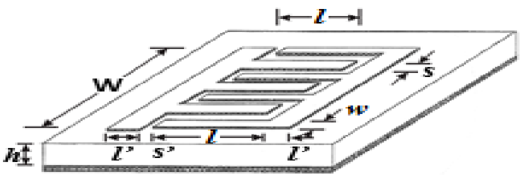


Figure 2.5: Interdigital Capacitor (Bahl, 2003)

The size can be reduced by reducing the dimensions of the structure or by using a high dielectric constant value substrate. Increasing the dielectric constant of the medium a hundred-fold will reduce the component dimensions by a factor of 10 (Bahl, 2003). The *Q*-factor of Interdigital Capacitors (IDC) can be enhanced by using high-conductivity conductors, low-loss tangent dielectric materials, suspended substrate, multilayer structure, and micromachining. The micromachining approach reduces the parasitic capacitance by a factor of ε_r and results in better millimetre-wave circuits. The parasitic associated with Interdigital Capacitors can be ignored as long as the Capacitance × Frequency product is smaller than 0.002. Additionally, by selecting the proper substrate thickness and air spacing between the substrate and ground plane, one can reduce the capacitor loss by a factor of 25 % to 50 %.

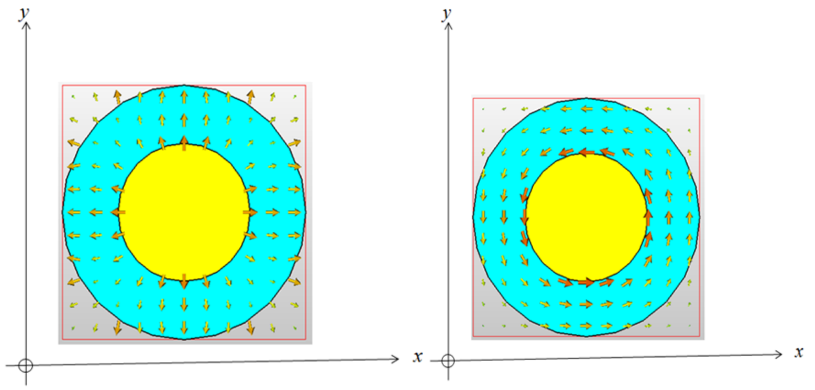
2.5 Design Basics of the Quasi-Lumped Resonator Antenna

2.5.1 Introduction

The theoretical explanation of the feeder characteristics in terms of the input impedance of coaxial feed probe, the circuit diagram, and all necessary circuit parameter equations were discussed. The effect of coaxial feed probe specifications in terms of its radii and height coupled with the substrate thickness effect on antenna performance were described. The field configuration, resonant mode, and resonant frequency as a result of coaxial feed probe were also discussed and presented.

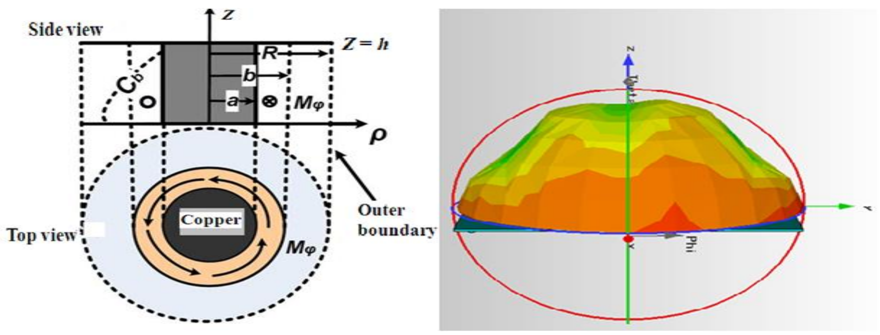
2.5.2 Coaxial Feed Line

A coaxial feed probe exciting the proposed antenna can be seen as mode-converter which converts the TEM mode across the probe aperture into the parallel plate mode. However, though the higher-order parallel plate modes are usually evanescent (a vanishing near-field standing wave) waves is localized in the vicinity of the probe, the zero-order parallel plate mode can propagate away (Hu et al, 2012).



(a) (b)

Figure 2.6: The Field Flow through the Probe Aperture. (a) Electric, (b) Magnetic



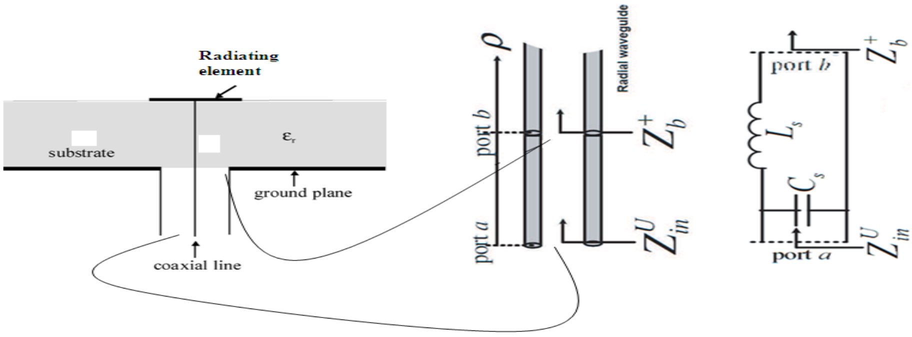
(a) (b)

Figure 2.7: Coaxial Probe Effect. (a) Coaxial Structure (Yaojiang et al, 2008), (b) 3-D Radiation

It is this zero-order mode that excite TM_{10} resonant mode of the quasi-lumped element resonator antenna and thus radiates into the surrounding as shown in Figure 2.6 and 2.7(b). Figure 2.7(a) shows the top and side view of the coaxial probe structure.

2.5.2.1 Equivalent Circuit Characteristics of the Coaxial Feed Probe

The equivalent circuit of the coaxial feed probe can be characterized into two parts namely: the coaxial port and the radial port shown in Figure 2.8 and explained in detail in Figure 2.9. Alternatively, the probe can be described as two-port network with a coaxial part and the radial part. There are three widely used probe feedings models for patch antennas and they were reported by Hu et al, (2012). The first one shown in Figure 2.10(a) is referred to as uniform-current model.



(a) (b) (c)

Figure 2.8: The Coaxial Probe Representation. (a) Coaxial Probe (Ning et al, 2006), (b) Radial Waveguide, (c) Circuit of the Radial Waveguide (Hu et al, 2012)

Above all, it can predicts the radiation pattern correctly, but deficient in accurately predicting the input impedance for a probe-fed microstrip patch antenna with thick substrate (Davidovitz & Lo, 1986). The magnetic-frill model shown in Figure 2.10(b) is the second model and often regarded as the most accurate probe feeding model for both the radiation pattern and as well as the input impedance. However, magnetic-frill model is significantly more complicated and usually requires a lot of computing resources.

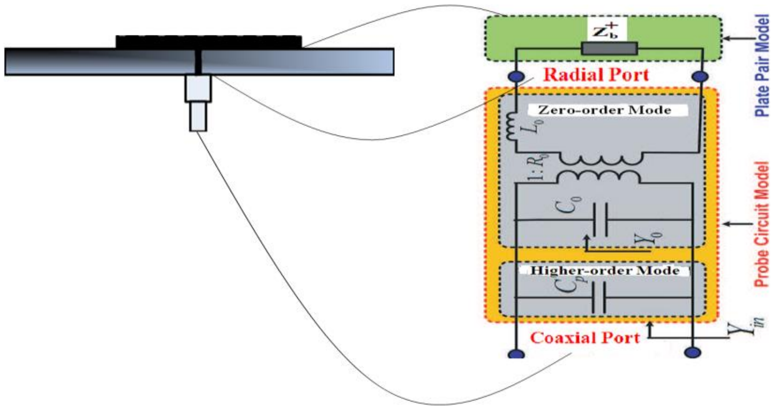


Figure 2.9: The Equivalent Circuit and the Coaxial Probe Representation (Hu et al, 2012)

Usually, one end is shortening to the ground plate and the other end having a small gap to the resonator as shown in Figure 2.9(b). A constant gap voltage source is impressed to excite both zero- and higher-order parallel plate modes. In this model, a constant source, unlike the space-varied source in the magnetic-frill model, was used. A notable setback of the gap-feed model is that the model is still faced with difficulties in computational resources and mesh generations as obtainable in the magnetic-frill model.

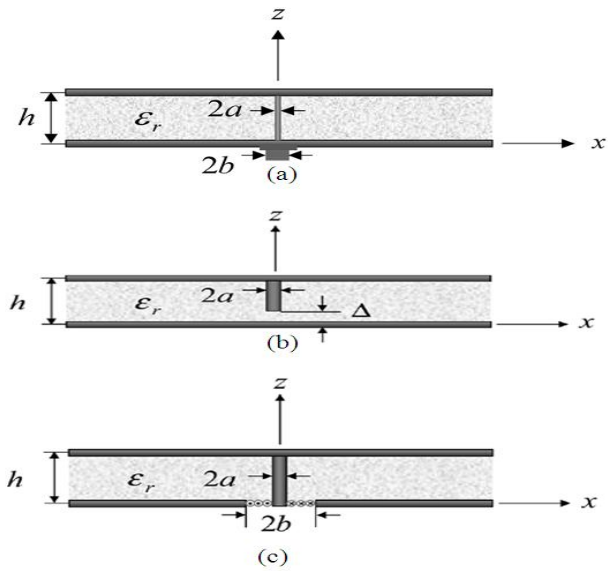


Figure 2.10: The Probe in An Infinite Parallel-Plate Waveguide. (a) Coaxial Probe, (b) Gap-Voltage Source, (c) Magnetic-Current Frill (Xu et al, 2005)