UNIVERSITI PUTRA MALAYSIA

MICROSTRIP TECHNIQUE AND MODELING FOR DETERMINATION OF MICROWAVE PROPERTIES OF Ni-Zn FERRITE

FAHMIRUDDIN ESA

FS 2015 68

MICROSTRIP TECHNIQUE AND MODELING FOR DETERMINATION OF MICROWAVE PROPERTIES OF Ni-Zn FERRITE

By

FAHMIRUDDIN ESA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

January 2015

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

MICROSTRIP TECHNIQUE AND MODELING FOR DETERMINATION OF MICROWAVE PROPERTIES OF Ni-Zn FERRITE

By

FAHMIRUDDIN ESA

January 2015

Chairperson : Associate Professor Zulkifly Abbas, PhD

Faculty : Faculty of Science

Ni-Zn ferrite has been such important topics since 1900 but the reported works are mainly discussed on the sample preparation technique also microstructural and morphological analysis. Even though microwave properties of Ni-Zn ferrite have also been discovered by various workers using waveguide technique however air gap problems are still remain as the major issues. Furthermore, the effect of different Ni-Zn ratio in $Ni_xZn_{1-x}Fe_2O_4$ on the reflection, transmission and absorption properties in a wideband and higher frequency using microstrip technique has not been investigated. This thesis describes a detailed study on the application of a microstrip technique to determine the microwave properties of $Ni_xZn_{1-x}Fe_2O_4$ in the frequency range between 1 GHz and 10 GHz. The *x* compositions of the spinel ferrite were 0.1, 0.3, 0.5, 0.7, 0.9. The $Ni_xZn_{1-x}Fe_2O_4$ samples were prepared by 10 hours sintering at 900°C with 4°C/min increment from room temperature. Particles showed phase purity and crystallinity in powder X-ray diffraction (XRD) analysis. Surface morphology measurement of Scanning Electron Microcopy (SEM) was conducted on the plane surfaces of the molded samples which gave information about grain morphology, boundaries and porosity. The tabulated grain size for all samples was in the range of 62 nm – 175 nm. Energy dispersive X-ray analysis (EDX) was done to confirm the elemental composition of the Ni-Zn ferrite samples by their weight and atomic percentage of each element for certain particular composition taken from specific area of the micrograph.

The transmission (S_{21}) and reflection (S_{11}) properties of the microstrip loaded with $Ni_xZn_{1-x}Fe_2O_4$ were extensively studied theoretically using finite element method. The microstrip measurements were conducted using a

HP8720B vector network analyzer. The electromagnetic field distribution of the microstrip covered with $Ni_{0.5}Zn_{0.5}Fe_2O_4$ sample was visualized using FEM software COMSOL. It was found that $Ni_xZn_{1-x}Fe_2O_4$ with higher values of x absorbed more microwave energy which in turn reduced the reflection and transmission coefficients. A good linear relationship was found between the absorption loss P_{loss} and fractional composition x at 3 GHz. The waves were totally absorbed by $Ni_xZn_{1-x}Fe_2O_4$ at frequencies above 7 GHz for $x \geq 0.5$. An optimization routine was also introduced in this work to determine both the permittivity and permeability of $Ni_{0.5}Zn_{0.5}Fe_2O_4$ sample by matching the theoretical and measured values of S_{11} and S_{21}. The complex permittivity and permeability of $Ni_{0.5}Zn_{0.5}Fe_2O_4$ sample along the frequency ranges were linked to the other findings. The measured S-parameters were compared with the results obtained using the Nicolson Ross Weir (NRW), Finite Element Method (FEM) and optimization method. The optimization method provides the highest accuracy when compared with the measured $|S_{11}|$ and $|S_{21}|$ with a mean error 0.0403 and 0.0177, respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KAEDAH MIKROSTRIP DAN PEMODELAN UNTUK MENENTUKAN SIFAT GELOMBANGMIKRO Ni-Zn FERRITE

Oleh

FAHMIRUDDIN ESA

Januari 2015

Pengerusi : Profesor Madya Zulkifly Abbas, PhD

Fakulti : Fakulti Sains

Ni-Zn ferit telah menjadi topik yang penting sejak tahun 1900 tetapi kerja-kerja yang dilaporkan adalah lebih kepada perbincangan mengenai teknik penyediaan bahan juga analisis struktur mikro dan morfologi. Walaupun ciri-ciri gelombang mikro telah dipelopori oleh pelbagai penyelidik dengan menggunakan teknik pandu gelombang namun masalah ruang udara adalah masih menjadi isu besar. Tambahan lagi, kesan nisbah Ni-Zn dalam $Ni_xZn_{1-x}Fe_2O_4$ terhadap ciri pantulan, penghantaran dan penyerapan dalam jalur lebar dan frekuensi tinggi menggunakan teknik mikrostrip belum lagi dikaji. Tesis ini memperihalkan kajian yang mendalam terhadap aplikasi teknik mikrostrip untuk menentukan ciri-ciri gelombang mikro bagi $Ni_xZn_{1-x}Fe_2O_4$ dalam frekuensi antara 1 GHz dan 10 GHz. Komposisi *x* bagi ferit spinel adalah 0.1, 0.3, 0.5, 0.7, 0.9. Sampel $Ni_xZn_{1-x}Fe_2O_4$ telah disediakan menggunakan kaedah pensinteran selama 10 jam pada suhu 900 ^oC dengan kadar kenaikan suhu sebanyak 4^oC/min dari suhu bilik. Zarah sampel yang terbentuk menunjukkan fasa keaslian dan penghabluran dalam analisis pembelauan sinaran-X (XRD). Pengukuran morfologi permukaan menggunakan imbasan elektron mikrofotokopi (SEM) telah dijalankan pada permukaan satah sampel yang telah diacukan untuk mendapatkan maklumat berkenaan morfologi, sempadan dan keliangan butiran. Saiz butiran untuk semua sampel adalah dalam lingkungan 62 nm – 175 nm. Analisis serakan tenaga sinaran-X (EDX) dijalankan untuk mengenalpasti komposisi unsur sampel Ni-Zn ferit berdasarkan peratusan berat dan atom untuk setiap unsur dalam komposisi tertentu yang diambil dari kawasan mikrograf yang spesifik.

Ciri penghantaran (S_{21}) dan pantulan (S_{11}) bagi mikrostrip yang berisi dengan sampel $Ni_xZn_{1-x}Fe_2O_4$ telah dikaji terperinci berdasarkan teori

menggunakan kaedah elemen terhingga (FEM). Pengukuran mikrostrip dijalankan dengan menggunakan HP8720B analisis rangkaian vektor (VNA). Taburan medan elektromagnetik bagi mikrostrip tertutup dengan sampel $Ni_{0.5}Zn_{0.5}Fe_2O_4$ telah digambarkan menggunakan perisian FEM COMSOL. Hasil kajian ini mendapati $Ni_xZn_{1-x}Fe_2O_4$ dengan nilai x yang tinggi menyerap lebih banyak tenaga gelombang mikro yang seterusnya merendahkan pekali pantulan dan penghantaran. Hubungan linear yang baik telah didapati antara kehilangan penyerapan P_{loss} dan pecahan komposisi x pada 3 GHz. Gelombang ini telah diserap sepenuhnya oleh $Ni_xZn_{1-x}Fe_2O_4$ pada frekuensi lebih daripada 7 GHz bagi sampel dengan $x \geq 0.5$. Rutin pengoptimuman turut dijalankan untuk menentukan ketelusan dan ketelapan sampel $Ni_{0.5}Zn_{0.5}Fe_2O_4$ dengan memadankan nilai S_{11} and S_{21} yang diperolehi daripada perkiraan dan pengukuran. Ketelusan dan ketelapan kompleks bagi sampel $Ni_{0.5}Zn_{0.5}Fe_2O_4$ sepanjang julat frekuensi telah dikaitkan dengan penemuan lain. S-parameter yang diperolehi daripada pengukuran dibandingkan dengan S-parameter yang diperolehi daripada Nicolson Ross Weir (NRW), kaedah elemen terhingga (FEM) dan kaedah pengoptimuman. Kaedah pengoptimuman memberi keputusan yang paling tepat apabila dibandingkan dengan $|S_{11}|$ dan $|S_{21}|$ dengan purata ralat masing-masing 0.0403 dan 0.0177.

ACKNOWLEDGEMENTS

Alhamdulillah, all praise is due to Allah on whom we ultimately depend for sustenance and with His blessing and mercy to allow me to finalize this thesis.

My sincere appreciation and gratitude goes to the chairperson of the supervisory committee, Assoc. Prof. Dr. Zulkifly Abbas for his continuous supervision, guidance, advice and support. This thesis would not be completed without his assistance and encouragement.

I am highly grateful for the love, care, prayers and unconditional supports from my beloved wife, parents, brothers and sisters. I cannot thank them enough for always been there for me through ups and downs.

I also would like to extend my gratitude to the members of supervisory committee, Assoc. Prof. Dr. Mansor Hashim and Prof. Dr. Mohd Maarof Moksin for their advices, supervisions and motivations.

Special appreciation is also extended to the Scholarship Division, Ministry of Higher Education for providing financial support to me during the whole course of the study through the Skim Latihan Akademik IPTA (SLAI) scholarship program.

Last but not least, I would like to thank staffs at Department of Physics, Faculty of Science and my colleagues for all supports, helps, discussions, ideas and interactions.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Zulkifly Abbas, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Mansor Hashim, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

Mohd Maarof Moksin, PhD
Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

BUJANG KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ___________________________ Date: ____________________

Name and Matric No.: ____

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS & SYMBOLS

EM	-	Electromagnetic
EMI	-	Electromagnetic interference
MHz	-	Megahertz
GHz	-	Gigahertz
AC	-	Alternating current
DC	-	Direct current
TVS	-	Transient voltage suppressor
FeO/Fe_2O_3	-	iron(II) oxide/hematite
Ni-Zn ferrite	-	Nickel zinc ferrite
Mn-Zn ferrite	-	Manganese zinc ferrite
Fe	-	Iron
Si	-	Silicon
$Ni_xZn_{1-x}Fe_2O_4$	-	Nickel Zinc Ferrite with fractional composition of x
x	-	Mole fraction
MNDT	-	Microwave Non-Destructive Technique
m	-	Meter
XRD	-	X-ray diffraction
SEM	-	Scanning Electron Microscopy
SEI	-	Secondary electron imaging
BEI	-	Backscattered electron imaging
EDX	-	Energy dispersive X-ray
FDTD	-	finite difference time-domain method
MoM	-	method of moment
FEM	-	finite element method
TEM	-	Transverse electromagnetic

NRW	-	Nicolson Ross Weir
FE	-	field emission
Ni	-	Nickel
Zn	-	Zinc
O	-	Oxide
eV	-	Electron volt
keV	-	Kilo electron volt
cm	-	Centimeter
mm	-	Milimeter
µm	-	Micrometer
nm	-	Nanometer
COMSOL	-	COMSOL Multiphysics®
NEC	-	Numerical electromagnetic computational
ε'	-	Dielectric constant
ε''	-	Dielectric loss factor
μ'	-	Permeability
μ''	-	Magnetic loss factor
ε	-	Complex permittivity
μ	-	Complex permeability
$\tan\delta$	-	Loss tangent
E	-	Electric field
H	-	Magnetic field
MUT	-	Material under test
S-parameters	-	Scattering parameters
RF	-	Radio frequency
TE	-	Transverse electric
TM	-	Transverse magnetic

RBC	-	Reflectionless boundary condition
ABC	-	Absorbing boundary condition
PML	-	Perfectly match layer
CEM	-	Computational electromagnetic
HFSS	-	High frequency structural simulator
TPNR	-	Thermoplastic natural rubber
PP	-	Polypropylene
NR	-	Natural rubber
LNR	-	Liquid natural rubber
RL	-	Reflection loss
PVC	-	Polyvinylchloride
dB	-	Decibel
PU	-	Polyurethane
PANI	-	Polyaniline
Li-Zn ferrite	-	Lithium zinc ferrite
RAM	-	Radar absorbing material
ε_{eff}	-	Effective permittivity
μ_{eff}	-	Effective permeability
ε_r	-	Relative permittivity
μ_r	-	Relative permeability
NOEs	-	Number of elements
PDE	-	Partial differential equation
S_{11}	-	Reflection coefficient
S_{21}	-	Transmission coefficient
$\lvert S_{11}\rvert$	-	Magnitude of reflection coefficient
$\lvert S_{21}\rvert$	-	Magnitude of transmission coefficient
$\emptyset S_{11}$	-	Phase angle of reflection coefficient

$\emptyset S_{21}$	-	Phase angle of transmission coefficient
Z_o	-	Characteristic impedance / characteristic impedance of the measurement system
Z_s	-	Input impedance
W	-	Width of the conductor line
h	-	Height of the substrate
d	-	Sample's height
l	-	Length of the substrate
L	-	Sample's length
τ_{meas}	-	Measured group delay
λ	-	Wavelength
f	-	Frequency
kV	-	Kilovolt
mA	-	Miliampere
d_{hkl}	-	Distance between lattices
θ	-	Diffraction angle
a	-	Cell perimeter (lattice constant)
D_x	-	X-ray density
M	-	Molecular mass
N	-	Avogadro's number
DXF	-	Drawing Exchange Format
VNA	-	Vector Network Analyzer
PEC	-	Perfect electric conductor
JCPDS	-	Joint Committee on Powder Diffraction Standards
Å	-	Angstrom

CHAPTER 1

INTRODUCTION

Electromagnetic (EM) waves at microwave frequencies have found many applications in various fields such as wireless telecommunication system, radar, local area network, electronic devices, mobile phones, laptops and medical equipment (Lim et al., 2003; Maeda et al., 2004; Jing et al., 2009; Lakshmi et al., 2009). The effect of growth in various applications has led to many electromagnetic interference (EMI) problems that has to be suppressed to acceptable limits. EMI reducing materials (absorbers) may be dielectric or magnetic (Grimes and Grimes, 1993) and the design depends on the frequency range, the desired quantity of shielding and the physical characteristics of the devices being shielded. This EMI could be suppressed by using ferrite materials (magnetic absorbers) due to their various electrical and magnetic properties. A case study on the development of EMI shielding ferrite has been made by Chandran and Cursetji (1999). Thus it is important to determine their high frequency characteristics for the applications of EM in the high GHz ranges (Arshak et al., 2001; Da Silva and Mohallem, 2001; Zabetakis et al., 2005; Hwang, 2006).

1.1 EMI Shielding Materials

EMI shielding and suppression materials can be broadly categorized into three groups (Ramasamy, 1997); EMI shielding materials, surge or transient suppression components and EMI filter materials. The EMI shielding is the use of conductive materials such as copper, aluminum, silver and nickel in the form of adhesive tape or paint coatings to reduce radiated EMI reflection or absorption. It is used for a wide variety of commercial/military EMI shielding applications.

The second category is briefly explained in the transient voltage protection for alternating current (AC) and direct current (DC) power circuits. Circuits or devices protection against high voltage transients or surges of thousands volts caused by lightning strike are intensely needed. Electronic system might be damaged by the unexpected change in voltages if proper protection is not provided. Suppression components such as gas diodes, silicon varistors, metal oxide varistors, transient voltage suppressor (TVS) diodes and clamping principles may be connected indirectly in parallel circuits using decoupling impedances in order to achieve good protection to the circuit.

Low pass EMI filters are used to attenuate conducted noise currents in variety of applications including shielded enclosures and other electrical or electronic subsystems. Application of filter is very important, whether to protect the equipment form incoming interference or to suppress the interference generated by the equipment to minimum level or to protect the signal lines. The performance of the filter is being judged by its insertion loss and attenuation characteristics. Lossy line or dissipative filters can perform well at high frequency (500 MHz to 10 GHz) and have the great advantage of removing the noise energy in the form of heat. Ferrite beads and ferrite rod are the example of lossy line EMI absorptive filters.

The shielding property of the ferrite is strongly influenced by the process parameters and microstructure (Chandran and Cursetji, 1999). The properties of ferrites which strongly influence the EMI suppression capability include the chemical composition, crystalline structure, grain size, nature of porosity, thickness of grain boundary and magnetocrystalline anisotropy. Each of this property shows an important role in the end properties of the ferrites and thus necessitates fine tuning of each of these to suit the end applications.

1.1.1 Magnetic Absorber

Ferrites are metallic oxides that contain iron for example that occur in nature and have been known as hematite. The divalent iron (FeO) contains two electrons and the trivalent iron (Fe_2O_3) contains three electrons with uncompensated magnetic moments. In magnetite, half the trivalent iron occupies a type A crystallographic sites while the divalent iron and the rest of the trivalent iron occupy type B crystallographic sites. At zero Kelvin all moments at a given type site are aligned parallel, and the two types of sites are antiparallel with each other. The result is the net magnetic moment of the divalent iron. Because of the cancellation and dilution by oxygen, the magnetic moment is much smaller than for the metals. The permeability is therefore also much less. Since hematite is conductive, it is not suitable to be as an absorber. Useful material has the divalent iron replaced by another divalent metal; a common one is a mixture of nickel and zinc. Spinel material is cubic and moments are initially in equivalent crystallographic directions.

1.1.2 Nickel Zinc Ferrite

Nickel Zinc Ferrite (Ni-Zn ferrite), together with manganese zinc ferrites (Mn-Zn ferrite) is a major member of spinel ferrite family. The spinel ferrites can be magnetized or demagnetized easily by externally applied magnetic fields indicating that they have soft magnetic behavior. In addition, they have good magnetic properties with enhanced performance when compared to metallic magnets such as Fe and layered Fe-Si alloys (Sugimoto, 1999). Besides, they have high electrical resistivity, high magnetic permeability and possible modification of intrinsic properties over wide spectrums which enable them to be used as ceramic materials (Hench and West, 1990).

Ni-Zn ferrite ceramics are the preferred ceramic material for high frequency applications in order to suppress generation of Eddy current (Verma et al. 1999). Although Ni-Zn ferrite ceramics have high electrical resistivity to prevent Eddy current generation, they have moderate magnetic permeability compared to Mn-Zn ferrites. However, the electrical and magnetic properties of these ferrite ceramics are heavily influenced by its microstructural features such as grain size, the nature of grain boundaries and the extent and nature of porosity. The microstructural features of interest could be attained via chemical composition and high temperature processing (Jonker and Stuijts, 1971).

The aim of this study is to determine electromagnetic properties of Ni-Zn ferrites prepared at different chemical composition based on chemical formula $Ni_xZn_{1-x}Fe_2O_4$ with $0.1 \leq x \leq 0.9$ that sintered at constant temperature. The variations in the microstructures, elemental composition and alterations in scattering parameters as well as their electromagnetic properties of the Ni-Zn ferrites are the concern of this study.

1.2 An Overview of Microwave Technique

Microwave Non-Destructive Technique (MNDT) has been used effectively to measure electromagnetic materials. The technique was firstly described in the early 1950’s and since then many studies being published. Before this time, there was no equipment for the measurement of such short electromagnetic waves. The research and development in this technique enable the measurement of electromagnetic materials at higher microwave frequencies using more reasonable and robust generators.

The technique allows the measurement of electromagnetic materials at the microwave region with frequency and wavelength approximately between 300 MHz to 300 GHz and 10^{-3} and 10^{-1} m, respectively (Ida, 1992). The measurement is only limited to non-conducting material since MNDT has minimal penetration in good conducting material. However, microwaves are affected by a large number of material properties. The properties that can be measured by MNDT in lossless or lossy dielectrics are material composition, uniformity of the material, moisture and contamination content and other varied properties such as porosity.

Other conventional technique is filling a section of a standard closed transmission line such as a waveguide to measure microwave permittivity and permeability (Singh et al., 2000; Sharma and Afsar, 2011; Bayrakdar, 2011). However, this technique requires several types of sample preparation upon the measurement across the frequency ranges such as from 1.7 to 12.4 GHz. The frequency ranges include five frequency bands that are R (1.70-2.60 GHz), S (2.60-3.95 GHz), G (3.95-5.85 GHz), C (5.85-8.20 GHz) and X (8.20-12.40 GHz). Each band requires a different waveguide dimension and hence the volume of sample used also must be different for each band.

The other great measurement method in a wide band frequency for magnetic thin film materials is microstrip transmission method that have been studied by Saed (2005) and Wu et al. (2009) which the sample is deposited on rigid substrate. The microstrip transmission method is one of planar transmission line method since the thin film materials can be easily loaded in the measurement test fixture. The microstrip transmission line is based on a reflection and transmission technique adapted to a two port microstrip transmission line (Liu et al., 2005). The permittivity and permeability of the thin film can be determined by analyzing the full S-parameters of the two ports.

The microstrip line technique is easy to use, quick, non-destructive and has high sensitivity and accuracy especially for practical routine work. In addition, it should be able to measure samples with small and large cross section.

1.3 Microwave Characterization Techniques

Microwave behaves similar to light wave in terms of travel in straight lines, refract, reflect, diffract, scatter and interfere according to the same physical length. The only difference between them is a wavelength. The wavelength of microwave is usually 10^5 larger than the wavelength of light wave. Therefore, the microwave tends to interact with materials and structures on a macroscopic scale. For instance, microwaves are capable of penetrating most nonmetallic materials, reflecting and scattering from internal boundaries and interacting with molecules (Bahr, 1982).

The interaction between microwaves and materials can be deduced from Maxwell's equations and material properties. The relations define a variety of properties such as mode of propagation, reflection, refraction, transmission and impedance. Both permittivity and permeability are complex numbers of which the imaginary part is associated with losses. This rich and complex system of properties allows a very wide range of measurement techniques at microwave frequencies. To date, many different methods have been proposed for microwave measurements of electromagnetic properties of material (Afsar et al., 1986; Ghodgaonkar et al., 1990; Queffelec et al., 1994; Baker-Jarvis et al., 1995; Faircloth et al., 2006).

1.4 Electromagnetic Modeling of Wave Interaction with Materials

The microwave sensor design problem is formally solved using the conventional analytical techniques but recently, some of numerical techniques have been utilized and mostly favored. This is due to the increase in computer's processor speed. Besides, the numerical methods are more accurate, easy and time saving compared to the traditional empirical modeling method which deals with many complex mathematic equations. Currently, variation of the numerical methods, such as finite difference time-domain method (FDTD), method of moment (MoM) and finite element method (FEM) are being commercialized. In this work, COMSOL interactive environment software for modeling and solving scientific and engineering problems is used. The software enables the visualization view of the system work which provides clear understanding about the designed working system. In this study, the FEM is used to separate the solution region of the designed open microstrip and fully covered microstrip into small elements. The FEM provides a clear contour of field distribution for both cases. The procedure of FEM simulation of the microstrip will be explained in Section 4.4.

1.5 Problem Statement

Ni-Zn ferrite has been a subject of intense research since 1900. However, the reported works were mainly on sample preparation techniques followed by conventional characterization techniques such as XRD, FESEM, SEM etc. Although microwave properties of Ni-Zn ferrite have also been investigated by various workers (Ma et al., 2008; Verma et al., 2003) but none has given a detailed description of Ni-Zn ferrite properties in a wide frequency range. The frequency limitation was due to the fact that different microwave techniques utilized different types of sample holder. At the lower end of the microwave frequencies (less than 1 GHz), the fixture holder is usually in the form of parallel plate. At higher frequencies, the closed coaxial and waveguide techniques are the most commonly used method to determine the transmission and reflection properties of materials. Both techniques are prone to measurement error due to the demand of fitting the samples snugly into the sample holder without leaving air gaps between the sample and the walls of the sample holder. An alternative solution is to measure the reflection coefficient of the sample using an open ended coaxial technique. Permittivity can be calculated from the measured reflection coefficient but the open ended coaxial technique could not provide information regarding the transmission and absorption properties of the sample. Microstrip techniques have also been used to measure permittivity and permeability of ferrites. However, the effect of different fractional composition *x* in Ni-Zn ferrite ($Ni_xZn_{1-x}Fe_2O_4$) on the transmission and absorption properties of the sample have not been investigated.

This thesis presents a detailed study on the effect of different composition of *x* in Ni-Zn ferrite overlay on the reflection, transmission and absorption of a microstrip transmission line in the frequency range from 1 GHz to 10 GHz. The mixing process of Ni-Zn ferrite samples were prepared using agate mortar and characterized using XRD, SEM and EDX. This work presents a pioneering study on the application of Finite Element Method (FEM) to calculate the scattering parameters of a microstrip covered with Ni-Zn ferrite. The effect of different values of *x* in $Ni_xZn_{1-x}Fe_2O_4$ on the reflection, transmission and absorption properties are experimentally investigated.

1.6 Objectives

The main objectives of this work are

1. To prepare Ni-Zn ferrite samples using conventional mixing process method according to $Ni_xZn_{1-x}Fe_2O_4$ formula ($0.1 \le x \le 0.9$) and characterize the structure and surface morphology of Ni-Zn ferrite by employing XRD and SEM as well as traced element identified by EDX.

2. To determine the complex permittivity of pure NiO, ZnO, Fe_2O_3 and $Ni_xZn_{1-x}Fe_2O_4$ in the frequency range between 1 GHz and 10 GHz.

3. To clarify the variation in S_{11} and S_{21} with frequency for an open microstrip and covered microstrip on the effect of different fractional composition x in Ni-Zn ferrite in the range frequency of 1 – 10 GHz.

4. To clarify the relationship between power loss and fractional composition of x in $Ni_xZn_{1-x}Fe_2O_4$ as well as the electric and magnetic field distribution inside the Ni-Zn ferrite sample using FEM.

5. To estimate complex permittivity and permeability of Ni-Zn ferrite sample by applying an optimization procedure via MATLAB in conjunction with the comparison of the results of S_{11} and S_{21} for covered microstrip between measurements, Nicolson Ross Weir (NRW), FEM and optimization.

1.7 Thesis Outline

This thesis is divided into six chapters and six appendices. Chapter 1 is a general introduction to give an overview of microwave techniques, nickel zinc ferrite material, electromagnetic modeling of wave interaction with microstrip and characterization techniques involving morphological and electrical properties. This chapter also discusses the problem statements and research objectives in details.

Chapter 2 reviews on the crystal structure of spinel ferrites as well as the cation distribution. Several microwave measurement techniques for the determination of material electromagnetic properties including commercial coaxial probe, free space, resonant cavities, waveguide and coaxial line technique as well as their limitations. The chapter also gives an overview of microstrip transmission line technique and also the advantageous in performing microwave characterization measurement. Several numerical methods are also reviewed in the structure analysis including the basic procedure, advantage and limitations of each technique.

Chapter 3 presents a general survey on the characteristic impedance and effective permittivity for open microstrip using quasi-TEM approximation. Comparison of characteristic impedance calculated between quasi-TEM and FEM is shown to be in a good agreement. The calculation of characteristic impedance of covered microstrip is performed by finite element method (FEM). The calculation of reflection and transmission coefficients of the microstrip line is considered in wave approach. The FEM formulation applies to determine the reflection and transmission coefficient of the covered microstrip. The calculation of S_{11} and S_{21} are also been reviewed.

Details of sample preparation, structure characterization, surface morphology and S-parameters experimental setup using microstrip technique will be discussed in Chapter 4. This chapter also describes the implementation procedure of the covered microstrip that has been performed using COMSOL software.

Chapter 5 describes microstructural and electromagnetic characterization results in details. This chapter shows the results of comprehensive S-parameters (S_{11} and S_{21}) measurements for open microstrip as well as for microstrip covered with $Ni_xZn_{1-x}Fe_2O_4$ samples using Vector Network Analyzer 8720B (VNA). Permittivity of $Ni_xZn_{1-x}Fe_2O_4$ samples are also performed using Agilent Dielectric Probe Kit 85070B, which can be used as an initial guess in the optimization process. There are also comparisons of obtained S-parameters using NRW and FEM methods. An optimization procedure to improve NRW formulas and to determine S-parameters of $Ni_{0.5}Zn_{0.5}Fe_2O_4$ material by finding the best values of complex permittivity and permeability will be discussed in this chapter.

Finally, in Chapter 6, conclusions are drawn and suggestions are made for future research activities in this field.

REFERENCES

Abbas, S. M., Dixit, A. K., Chatterjee, R. and Goel, T. C. (2007). Complex permittivity, complex permeability and microwave absorption properties of ferrite–polymer composites. *Journal of Magnetism and Magnetic Materials*, *309*(1), 20-24.

Abbas, Z., Pollard, R. D. and Kelsall, R. W. (2001). Complex permittivity measurements at Ka-band using rectangular dielectric waveguide. *Instrumentation and Measurement, IEEE Transactions on*, *50*(5), 1334-1342.

Afsar, M. N., Birch, J. R., Clarke, R. N. and Chantry, G. W. (1986). The measurement of the properties of materials. *Proceedings of the IEEE*, *74*(1), 183-199.

Arshak, K. I., Ajina, A. and Egan, D. (2001). Development of screen-printed polymer thick film planner transformer using Mn–Zn ferrite as core material. *Microelectronics Journal*, *32*(2), 113-116.

Ayres, W. P., Vartanian, P. H. and Helgesson, A. L. (1958). Propagation in dielectric slab loaded rectangular waveguide. *Microwave Theory and Techniques, IRE Transactions on*, *6*(2), 215-222.

Azaroff, L. V., Kaplow, R., Kato, N., Weiss, R. J., Wilson, A. J. C. and Young, R. A. (1974). *X-ray Diffraction* (pp. 180-186). New York: McGraw-Hill.

Bahl, I. J. and Bhartia, P. (1980). Characteristics of inhomogeneous broadside-coupled striplines. *Microwave Theory and Techniques, IEEE Transactions on*, *28*(6), 529-535.

Bahr, A. J. (1982). *Microwave nondestructive testing methods*. New York: Gordon and Breach Science Publisher.

Baker-Jarvis, J., Vanzura, E. J. and Kissick, W. A. (1990). Improved technique for determining complex permittivity with the transmission/reflection method. *Microwave Theory and Techniques, IEEE Transactions on*, *38*(8), 1096-1103.

Baker-Jarvis, J., Jones, C., Riddle, B., Janezic, M., Geyer, R. G., Grosvenor Jr, J. H. and Weil, C. M. (1995). Dielectric and magnetic measurements: a survey of nondestructive, quasi-nondestructive, and process-control techniques. *Research in nondestructive evaluation*, *7*(2-3), 117-136.

Barton, M. L. and Cendes, Z. J. (1987). New vector finite elements for three-dimensional magnetic field computation. *Journal of Applied Physics*, *61*(8), 3919-3921.

Bayrakdar, H. (2011). Complex permittivity, complex permeability and microwave absorption properties of ferrite–paraffin polymer composites. *Journal of Magnetism and Magnetic Materials*, *323*(14), 1882-1885.

Blackham, D. V. and Pollard, R. D. (1997). An improved technique for permittivity measurements using a coaxial probe. *IEEE Transactions on Instrumentation and Measurement*, *46*(5), 1093-1099.

Bossavit, A. and Verite, J. C. (1982). A mixed FEM-BIEM method to solve 3-d eddy-current problems. *Magnetics, IEEE Transactions on*, *18*(2), 431-435.

Brent, R. P. (1971). An algorithm with guaranteed convergence for finding a zero of a function. *The Computer Journal*, *14*(4), 422-425.

Buchanan, R. C. (Ed.). (2004). *Ceramic materials for electronics* (Vol. 25). *CRC press*.

Burke, G. J., and Poggio, A. J. (1981). Numerical Electromagnetics Code (NEC) method of moments. Part III: User's guide. *NOSC technical document*, *116*.

Chandran, R. G., and Cursetji, R. M. (1999). Development of an EMI shielding ferrite: a case study. *Proceedings of the International Conference on Electromagnetic Interference and Compatibility'99* (pp. 380-383).

Chen, W. and Zhu, W. (2011). *Deposition of $CoFe_2O_4$ composite thick films and their magnetic, electrical properties characterizations* (pp. 109-129). INTECH Open Access Publisher.

Clark, D. E., Folz, D. C., Folgar, C. E. and Mahmoud, M. M. (2005). *Microwave solutions for ceramic engineers*. Wiley-American Ceramic Society.

Courant, R. (1943). Variational methods for the solution of problems of equilibrium and vibrations. *Bulletin of the American Mathematical Society*, *49*(1): 1-23.

Da Silva, J. B. and Mohallem, N. D. S. (2001). Preparation of composites of nickel ferrites dispersed in silica matrix. *Journal of Magnetism and Magnetic Materials*, *226*, 1393-1396.

Davidson, D. B. (2005). *Computational electromagnetics for RF and microwave engineering*. Cambridge University Press.

Deshpande, M. D., Tiemsin, P. I. and Cravey, R. (1997). A new approach to estimate complex permittivity of dielectric materials at microwave frequencies using waveguide measurements. *Microwave Theory and Techniques, IEEE Transactions on*, *45*(3), 359-366.

Dosoudil, R., Ušáková, M., Franek, J., Sláma, J. and Olah, V. (2006). RF electromagnetic wave absorbing properties of ferrite polymer composite materials. *Journal of Magnetism and Magnetic Materials*, *304*(2), e755-e757.

Faircloth, D. L., Baginski, M. E. and Wentworth, S. M. (2006). Complex permittivity and permeability extraction for multilayered samples using S-parameter waveguide measurements. *Microwave Theory and Techniques, IEEE Transactions on*, *54*(3), 1201-1209.

Gama, A. M., Rezende, M. C. and Dantas, C. C. (2011). Dependence of microwave absorption properties on ferrite volume fraction in MnZn ferrite/rubber radar absorbing materials. *Journal of Magnetism and Magnetic Materials*,*323*(22), 2782-2785.

Gedney, S. D. (2011). Introduction to the Finite-difference Time-domain (FDTD) Method for Electromagnetics. *Synthesis Lectures on Computational Electromagnetics*, *6*(1), 1-250.

George, P. L., Hecht, F. and Saltel, E. (1990). Automatic 3D mesh generation with prescribed meshed boundaries [alternator]. *Magnetics, IEEE Transactions on*, *26*(2), 771-774.

Ghodgaonkar, D. K., Varadan, V. V. and Varadan, V. K. (1990). Free-space measurement of complex permittivity and complex permeability of magnetic materials at microwave frequencies. *Instrumentation and Measurement, IEEE Transactions on*, *39*(2), 387-394.

Grimes, C. A. and Grimes, D. M. (1993). A brief discussion of EMI shielding materials. *14th IEEE Aerospace Applications Conference* (Vol. 1, pp. 217-226).

Gupta, K. C., Garg, R. and Bahl, I. J. (1979). *Microstrip lines and slotlines*. Dedham, MA : Artech House.

Harrington, R. F. and Harrington, J. L. (1996). *Field computation by moment methods*. Oxford University Press.

Hench, L. L., and West, J. K. (1990). *Principles of electronic ceramics*. John Wiley and Sons Publisher.

Mahmoud M. Hessien, Zaki I. Zaki, Al-Qahtani Mohsen, (2013) “Low-Temperature Synthesis of Nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ by Oxalate Precursor Route”, *Advances in Materials Physics and Chemistry, Vol. 3 Iss: 1A*. DOI:10.4236/ampc.2013.31A001

Hwang, Y. (2006). Microwave absorbing properties of NiZn-ferrite synthesized from waste iron oxide catalyst. *Materials Letters*, *60*(27), 3277-3280.

Ida, N. (1992). *Microwave NDT*. Dordrecht, Netherlands: Kluwer Academic Publishers.

Idris, F. M. (2012). *Fabrication and Characterization of Selected Microwave Absorbing Ferrite-Polymer Composites*. Master Thesis. Universiti Putra Malaysia.

Robiul Islam, Md Obaidur Rahman, M. Abdul Hakim, Dilip Kumar Saha, Saiduzzaman, Saroaut Noor, Md Al-Mamun, (2012) "Effect of sintering temperature on structural and magnetic properties of $Ni_{0.55}Zn_{0.45}Fe_2O_4$ ferrites", *Materials Sciences and Applications, Vol. 3 Iss. 5*. DOI:10.4236/msa.2012.35048

Janezic, M. D., Kuester, E. F. and Jarvis, J. B. (2004). Broadband complex permittivity measurements of dielectric substrates using a split-cylinder resonator. *Microwave Symposium Digest, 2004 IEEE MTT-S International* (Vol. 3, pp. 1817-1820).

Janezic, M. D., Williams, D. F., Blaschke, V., Karamcheti, A. and Chang, C. S. (2003). Permittivity characterization of low-k thin films from transmission-line measurements. *Microwave Theory and Techniques, IEEE Transactions on*,*51*(1), 132-136.

Jiang, C. and Yang, C. (1995). Complex permittivity and permeability measurements for high-loss material in a waveguide. *Microwave and Optical Technology Letters*, *9*(1), 41-43.

Jin, J. M. (2010). *Theory and Computation of Electromagnetic Fields*. Wiley-IEEE Press.

Jin, J. M. and Riley, D. J. (2009). *Finite element analysis of antennas and arrays*. Wiley-IEEE Press.

Jing, L., Wang, G., Duan, Y. and Jiang, Y. (2009). Synthesis and electromagnetic characteristics of the flake-shaped barium titanate powder. *Journal of Alloys and Compounds*, *475*(1), 862-868.

Jonker, G. H. and Stuijts, A. L. (1971). Controlling properties of electroceramic materials through their microstructure. *Philips Technical Review*, *32*(3-4), 79.

Kassem, H., Vigneras, V. and Lunet, G. (2010). Characterization techniques for materials' properties measurement. *Microwave and Millimeter Wave Technologies from Photonic Bandgap Devices to Antenna and Applications*, 289-314.

Komarov, V. V. and Yakovlev, V. V. (2003). Modeling control over determination of dielectric properties by the perturbation technique. *Microwave and Optical Technology Letters*, *39*(6), 443-446.

Kong, I., Hj Ahmad, S., Hj Abdullah, M., Hui, D., Nazlim Yusoff, A. and Puryanti, D. (2010). Magnetic and microwave absorbing properties of magnetite–thermoplastic natural rubber nanocomposites. *Journal of Magnetism and Magnetic Materials*, *322*(21), 3401-3409.

Kong, J., Liu, J., Wang, F., Luan, L., Itoh, M. and Machida, K. I. (2011). Electromagnetic wave absorption properties of Fe3O4 octahedral nanocrystallines in gigahertz range. *Applied Physics A*, *105*(2), 351-354.

Krishna, K. R., Kumar, K. V. and Ravinder, D. (2012). Structural and Electrical Conductivity Studies in Nickel-Zinc Ferrite. *Advances in Materials Physics and Chemistry*, *2*, 185.

Lakshmi, K., John, H., Mathew, K. T., Joseph, R. and George, K. E. (2009). Microwave absorption, reflection and EMI shielding of PU–PANI composite. *Acta Materialia*, *57*(2), 371-375.

Laurin, J., Tanneau, G. and Akyel, C. (1996). Waveguide permittivity measurement using variable-length samples and an uncalibrated reflectometer.*Instrumentation and Measurement, IEEE Transactions on*, *45*(1), 298-301.

Lee, W. E. and Rainforth, W. M. (1994). *Ceramic Microstructures: Property Control by Processing*. London: Chapman and Hall.

Lim, K. M., Kim, M. C., Lee, K. A. and Park, C. G. (2003). Electromagnetic wave absorption properties of amorphous alloy-ferrite-epoxy composites in quasi-microwave band. *Magnetics, IEEE Transactions on*, *39*(3), 1836-1841.

Liu, Q., Lv, L., Zhou, J. P., Chen, X. M., Bian, X. B. and Liu, P. (2012). Influence of nickel-zinc ratio on microstructure, magnetic and dielectric properties of $Ni_{(1-x)}Zn_xFe_2O_4$ ferrites. *Journal of Ceramic Processing Research*,*13*(2), 110-116.

Liu, Y., Chen, L., Tan, C. Y., Liu, H. J. and Ong, C. K. (2005). Broadband complex permeability characterization of magnetic thin films using shorted microstrip transmission-line perturbation. *Review of Scientific Instruments*, *76*(6), 063911.

Logan, D. L. (2012). *A first course in finite element method*. Stanford, Connecticut, USA: Cengange Learning.

Ma, R., Wang, Y., Tian, Y., Zhang, C. and Li, X. (2008). Synthesis, characterization and electromagnetic studies on nanocrystalline nickel zinc ferrite by polyacrylamide gel. *Journal of Materials Science and Technology*, *24*(3), 419-422.

Maeda, T., Sugimoto, S., Kagotani, T., Tezuka, N., and Inomata, K. (2004). Effect of the soft/hard exchange interaction on natural resonance frequency and electromagnetic wave absorption of the rare earth–iron–boron compounds. *Journal of Magnetism and Magnetic Materials*, *281*(2), 195-205.

Marin, S. P. (1982). Computing scattering amplitudes for arbitrary cylinders under incident plane waves. *Antennas and Propagation, IEEE Transactions on*, *30*(6), 1045-1049.

Mathew, K. T. and Raveendranath, U. (2000). Cavity perturbation techniques for measuring dielectric parameters of water and other allied liquids. *Sensors Update*, *7*(1), 185-210.

Meaney, P. M., Gregory, A. P., Epstein, N. R. and Paulsen, K. D. (2014). Microwave open-ended coaxial dielectric probe: interpretation of the sensing volume re-visited. *BMC medical physics*, *14*(1), 3.

Mei, K. K. (1974). Unimoment method of solving antenna and scattering problems. *Antennas and Propagation, IEEE Transactions on*, *22*(6), 760-766.

Moulson, A. J. and Herbert, J. M. (2003). *Electroceramics: materials, properties, applications*. John Wiley & Sons.

Moussy, J. B. (2013). From epitaxial growth of ferrite thin films to spin-polarized tunnelling. *Journal of Physics D: Applied Physics*, *46*(14), 143001.

Nicolson, A. M. and Ross, G. F. (1970). Measurement of the intrinsic properties of materials by time-domain techniques. *Instrumentation and Measurement, IEEE Transactions on*, *19*(4), 377-382.

Peng, J., Balanis, C. A. and Barber, G. C. (1993). NEC and ESP codes: Guidelines, limitations, and EMC applications. *Electromagnetic Compatibility, IEEE Transactions on*, *35*(2), 124-133.

Qian, K., Seah, H. S. and Asundi, A. K. (2003). Algorithm for directly retrieving the phase difference: a generalization. *Optical Engineering*, *42*(6), 1721-1724.

Qiu, J., Shen, H. and Gu, M. (2005). Microwave absorption of nanosized barium ferrite particles prepared using high-energy ball milling. *Powder technology*, *154*(2), 116-119.

Queffelec, P., Gelin, P., Gieraltowski, J. and Loaec, J. (1994). A microstrip device for the broad band simultaneous measurement of complex permeability and permittivity. *Magnetics, IEEE Transactions on*, *30*(2), 224-231.

Ramasamy, S. R. (1997). A review of EMI shielding and suppression materials. *Proceedings of the International Conference on Electromagnetic Interference and Compatibility'97* (pp. 459-466).

Matli Penchal Reddy, Il Gon Kim, Dong Sun Yoo, Wuppati Madhuri, Nagireddy Ramamanohar Reddy, Kota Venkata Siva Kumar, Rajuru Ramakrishna Reddy, (2012) "Characterization and electromagnetic studies on NiZn and NiCuZn ferrites prepared by microwave sintering technique", *Materials Sciences and Applications, Vol. 3 Iss. 9*. DOI:10.4236/msa.2012.39091

Roberts, S. and Von Hippel, A. (1946). A new method for measuring dielectric constant and loss in the range of centimeter waves. *Journal of Applied Physics*, *17*(7), 610-616.

Sadiku, M. N. (2000). *Numerical techniques in electromagnetics*. Florida: CRC Press.

Saed, M. A. (2005). Reconfigurable broadband microstrip antenna fed by a coplanar waveguide. *Progress In Electromagnetics Research*, *55*, 227-239.

Schneider, M. V. (1969). Microstrip lines for microwave integrated circuits. *Bell System Technical Journal*, *48*(5), 1421-1444.

Sharma, A., and Afsar, M. N. (2011). Microwave complex permeability and permittivity of nanoferrites. *Journal of Applied Physics*, *109*(7), 07A503.

Singh, P., Babbar, V. K., Razdan, A., Puri, R. K. and Goel, T. C. (2000). Complex permittivity, permeability, and X-band microwave absorption of CaCoTi ferrite composites. *Journal of Applied Physics*, *87*(9), 4362-4366.

Sucher, M. and Fox, J. (1963). *Handbook of microwave measurements*. Vol. II, New York:Wiley.

Sugimoto, M. (1999). The past, present, and future of ferrites. *Journal of the American Ceramic Society*, *82*(2), 269-280.

Taflove, A. and Brodwin, M. E. (1975). Numerical solution of steady-state electromagnetic scattering problems using the time-dependent Maxwell's equations. *Microwave Theory and Techniques, IEEE Transactions on*, *23*(8), 623-630.

Ting, T. H., Yu, R. P. and Jau, Y. N. (2011). Synthesis and microwave absorption characteristics of polyaniline/NiZn ferrite composites in 2–40 GHz. *Materials Chemistry and Physics*, *126*(1), 364-368.

Varadan, V. V., Jose, K. A. and Varadan, V. K. (2000). In situ microwave characterization of nonplanar dielectric objects. *Microwave Theory and Techniques, IEEE Transactions on*, *48*(3), 388-394.

Verma, A., Goel, T. C., Mendiratta, R. G. and Gupta, R. G. (1999). High-resistivity nickel–zinc ferrites by the citrate precursor method. *Journal of Magnetism and Magnetic Materials*, *192*(2), 271-276.

Verma, A., Saxena, A. K. and Dube, D. C. (2003). Microwave permittivity and permeability of ferrite–polymer thick films. *Journal of magnetism and magnetic materials*, *263*(1), 228-234.

Wei, C., Shen, X., Song, F., Zhu, Y. and Wang, Y. (2012). Double-layer microwave absorber based on nanocrystalline $Zn_{0.5}Ni_{0.5}Fe_2O_4$/α-Fe microfibers. *Materials & Design*, *35*, 363-368.

Wu, Y., Tang, Z. X., Xu, Y. and Zhang, B. (2009). Measure the complex permeability of ferromagnetic thin films: Comparison shorted microstrip method with microstrip transmission method. *Progress In Electromagnetics Research Letters*, *11*, 173-181.

Yusoff, A. N., Abdullah, M. H., Ahmad, S. H., Jusoh, S. F., Mansor, A. A. and Hamid, S. A. A. (2002). Electromagnetic and absorption properties of some microwave absorbers. *Journal of Applied Physics*, *92*(2), 876-882.

Zabetakis, D., Dinderman, M., and Schoen, P. (2005). Metal-coated cellulose fibers for use in composites applicable to microwave technology. *Advanced Materials*, *17*(6), 734-738.

Zabotto, F. L., Gualdi, A. J., Eiras, J. A., Oliveira, A. J. A. D. and Garcia, D. (2012). Influence of the sintering temperature on the magnetic and electric properties of $NiFe_2O_4$ ferrites. *Materials Research*, *15*(3), 428-433.

Zheng, H., Yang, Y., Zhou, M., and Li, F. (2009). Microwave absorption and Mössbauer studies of Fe_3O_4 nanoparticles. In *ISIAME 2008* (pp. 131-136). Springer Berlin Heidelberg.

Zhou, J. M., Zhou, K. D. and Shao, K. R. (1992). Automatic generation of 3D meshes for complicated solids. *Magnetics, IEEE Transactions on*, *28*(2), 1759-1762.