



Cairo University

WAVEGUIDE MINIATURIZATION USING NEGATIVE PERMEABILITY METAMATERIAL (ANALYSIS AND APPLICATION)

By

Abdelmoniem Mohamed Alaa Eldeen Abdelmoniem

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Electronics and Communications Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

2018

**WAVEGUIDE MINIATURIZATION USING NEGATIVE
PERMEABILITY METAMATERIAL
(ANALYSIS AND APPLICATION)**

By
Abdelmoniem Mohamed Alaa Eldeen Abdelmoniem

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Electronics and Communications Engineering

Under the Supervision of

Prof. Dr. Mostafa El Said Mostafa

Prof. Dr. Samir F.Mahmoud

.....
Professor of Electromagnetic Waves
Electronics and Communications
Department
Faculty of Engineering, Cairo University

.....
Professor of Electromagnetic Waves
Electronics and Communications
Department
Faculty of Engineering, Cairo University

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT**

2018

**WAVEGUIDE MINIATURIZATION USING NEGATIVE
PERMEABILITY METAMATERIAL
(ANALYSIS AND APPLICATION)**

By
Abdelmoniem Mohamed Alaa Eldeen Abdelmoniem

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Electronics and Communications Engineering

Approved by the
Examining Committee

Prof. Dr. **Esmat Abd ELfatah Abd Allah** (External Examiner)
(Professor in Electronics Research Institute)

Prof. Dr. **Tamer Mostafa Abu ELfadl** (Internal Examiner)

Prof. Dr. **Mostafa El Said Mostafa** (Main Supervisor)

Prof. Dr. **Samir Fahmy Mahmoud** (Supervisor)

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

Engineer: Abd Elmoniem Mohamed Alaa Eldien Abdelmoniem Hassan
Date of Birth: 10 /6 /1988
Nationality: Egyptian
E-mail: eng_abdelmoniem_alaa@yahoo.com
Phone. : 0122-7032490
Address: 2 St. Mohamed Khatab- Maryotaya – Haram- Giza
Registration Date: 1 /3 / 2013
Awarding Date: / /
Degree: Master of Science
Department: Electronics and Communication (Waves)



Examiners: Prof. Dr. Esmat Abd Elfatah Abd Allah (External examiner)
(Professor in Electronics Research Institute)

Prof. Dr. Tamer Mostafa Abu ELfadal (Internal examiner)

Supervisors: Prof. Dr. Mostafa Elsaid Mostafa (Main Supervisor)
Prof. Dr. Samir Fahmy Mahmoud (Supervisor)

Title of Thesis:

Waveguide Miniaturization Using Negative Permeability Metamaterial
(Analysis and Application)

Key Words:

Negative transverse permeability, Metamaterials, Backward Waves,
Miniaturization of Waveguide, and Propagation below cut off.

Summary:

This research aims to study and analyze the electromagnetic phenomena of media with negative transverse permeability and how this leads into some physical phenomena such as the appearance of backward waves and the propagation below cutoff. This study and analysis is through the use of metamaterials of split ring resonator. The research has evidenced that the waveguide size can be miniaturize to smaller than its half. Also, the research has proved that the analytical determination of the electric and magnetic field inside the waveguide with the presence of the slab of dielectric permittivity and negative transverse permeability, and experimental Results of each case are shown clearly. Finally, it was shown how to achieve a high magnetic dipole to increase the negative transverse permeability, so that the losses can be decreased for a wider backward wave band.

ACKNOWLEDGEMENT

All gratitude and thanks to Allah, our lord, for his countless blessings bestowed on me including the conduct and completing the research of this thesis. I would also like to thank all people who helped me throughout the different stages of my thesis. First of all, I would like to express my gratitude to both **Professor Mostafa Elsaid** and **Professor Samir Fahmy** for the continuous support on the development of this work. Without their help, suggestions, comments and share of knowledge from these two professors the realization of this dissertation would not be possible.

I also want to thank my family and friends who have always supported me.

TABLE OF CONTENTS

Content	Page No.
Acknowledgement.....	i
Table of Contents	ii
List of Figures	iv
List of Tables	viii
List of Abbreviations	ix
List of Symbols.....	x
Abstract	xi
 CHAPTER ONE: INTRODUCTION	
1.1 Historical Background	1
1.2 Research Objectives	2
1.3 Research Structure	2
 CHAPTER TWO: LITERATURE REVIEW	
2.1 Introduction.....	3
2.2 Rectangular Waveguide	3
2.3 The Main Ways for Miniaturization of Waveguide.....	4
2.4 Synthesis of Negative Magnetic Permeability.....	5
2.5 Edge-Coupled Split Ring Resonator (EC-SRR)	6
2.6 Approximate Analysis of the Split Ring Resonator Particle	7
2.7 Bianisotropy Problem of Edge Coupled Split Ring Resonator Design.....	8
2.8 Avoiding Bianisotropy	9
2.9 The Broadside-Coupled SRR	9
2.10 Design of Split Ring Resonator	10
2.11 Theoretical Analysis	11
2.12 Experiment and Measurements	14
2.13 Summary	15
 CHAPTER THREE: ANALYSIS FOR THE PROPAGATION BELOW CUTOFF RESULTING FROM NEGATIVE PERMEABILITY OF SPLIT RING RESONATOR.....	
3.1 Introduction	17
3.2 Extraction of the Polarizability Tensors	17
3.3 Analysis of a Waveguide Loaded by a Slab of Negative Transverse Permeability	18
3.3.1 The Electric Field Distribution	19
3.3.2 The Magnetic Field Distribution	20
3.3.3 Dependence of Propagation Constant on Frequency.....	21
3.4 Applying Equations 2.20 to 2.26 p.17&18 on proposed design for the Split Ring Resonator (Numerical Calculation):.....	21
3.5 Results using CST-Studio Simulator.....	22

3.5.1 Design of a single BC-SRR at resonance frequency at 7.8GHZ	22
3.5.2 The Changes of Resonance Frequency According To The Changes In Radius Dimensions.....	22
3.5.3 Verifying The Review Results	23
3.6 Experimental Determination of the Frequency of Resonance, And Demonstration of Cross-Polarization Effects in the Edge Coupled Split Ring Resonator	25
3.6.1 Results of S_{21} by Simulation	25
3.7 Experimental determination of the frequency of resonance, and demonstration of cross-polarization effects in the BC-SRR.....	28
3.7.1 Results of S_{21} for each position in by Simulation	29
3.8 Prove of the Backward and Forward Wave	31
3.8.1 Pass-band in (x-direction)	31
3.8.2 Pass-band in (Z-direction)	32
3.9 Summary and Conclusion	32
CHAPTER FOUR: DESIGN & RESULTS	
4.1 Introduction	33
4.2 The Proposed design	33
4.3 Analysis of two Slabs located in waveguide.....	34
4.3.1 The electric field distribution ($m/a=0.2$)	36
4.3.2 The magnetic field distribution ($m/a=0.2$)	36
4.3.3 The electric field distribution with imaginary k_{xo} ($m/a=0.2$)	37
4.3.4 The propagation constant β versus frequency ($m/a=0.2$).....	37
4.4 Results using CST-Studio simulator	38
4.4.1 Edge coupled Split Ring Resonator	38
4.4.2 Design at resonance frequency $f_o=8.6$ GHz.....	41
4.4.3 Single Split Ring Resonator	41
4.5 Additional advanced function of the Proposed Design	46
4.6 Summary and Conclusion	46
CHAPTER FIVE: SUMMARY, CONCLUSION, AND RECOMMENDATIONS.....	
5.1 Summary and Conclusion	47
5.2 Recommendations for Future Research.....	48
Reference.....	49
Appendices	
Appendix A	51
Appendix B	53

LIST OF FIGURES

Figure No.	Figure Description	Page No.
1.1	Material classifications	1
2.1	Empty waveguide	3
2.2	Magnetic field is generated using an Alternating Current (AC) source connected to the coil	5
2.3	Edge-Coupled Split ring resonator	6
2.4	(a) Sketch of the EC-SRR. (b) Equivalent circuit. (c) Plots of the angular dependence of currents on the inner ring (dashed line), on the outer ring (dash-dotted line), and of the total current on both rings (solid line). (d) Plots of the angular dependence of the voltage on the inner ring (dashed line) and on the outer ring (dash-dotted line)	6
2.5	Illustration of Edge coupled split ring resonator	8
2.6	Modified split ring resonator or Broadside coupled split ring resonator BC-SRR	9
2.7	(a) BC-SRR (b) EC-SRR	10
2.8	Simple equivalent circuit for Broadside coupled split ring resonator	10
2.9	(a) The waveguide filled with the split ring resonators. (b) The unit cell.	11
2.10	Definition of the equivalent parallel plate waveguide problem	12
2.11	The influence of the filling material on wave propagation in a waveguide	13
2.12	Measurement of S_{21} , A stop band appeared at resonance frequency $f_o=7.8$ GHz, for a waveguide of $a=35$ mm filled with a metamaterial based on double split rings resonator, where $f_c < f_o$.	14
2.13	Measurement of S_{21} , A pass band appeared at resonance frequency $f_o=7.8$ GHz, for a waveguide of $a=12$ mm filled with a metamaterial based on double split rings resonator, where $f_c > f_o$.	15
3.1	A waveguide filled with a single slab located in symmetry along the waveguide	18
3.2	The electric field distribution versus waveguide width a , ($a=12$ mm) and ($d=0.74$ mm) at $f_o=7.8$ GHz	20

3.3	The magnetic field distribution versus waveguide width a , ($a=12\text{mm}$) and ($d=0.74\text{mm}$) at $f_o=7.8\text{ GHz}$	20
3.4	The propagation constant β/k_o versus resonance frequency f_o	21
3.5	Result of S_{21} versus frequency, the resonance frequency $f_o = 7.8\text{ GHz}$.	22
3.6	Result of S_{21} for difference inner radius of BC-SRR with frequency	22
3.7	Result of S_{21} , A stop band appeared at resonance frequency $f_o=7.8\text{ GHz}$, for a waveguide of $a=35\text{mm}$ filled with a metamaterial based on double split rings resonator, where $f_c < f_o$.	23
3.8	Result of S_{21} , A pass band appeared at resonance frequency $f_o=7.8\text{ GHz}$, for a waveguide of $a=12\text{mm}$ filled with a metamaterial based on double split rings resonator, where $f_c > f_o$.	24
3.9	Result of S_{21} , A pass band appeared at resonance frequency $f_o=7.8\text{ GHz}$, for a waveguide of $a=12\text{mm}$ filled with a metamaterial based on double split rings resonator taking losses into account, where $f_c > f_o$.	24
3.10	The four possible positions of Edge coupled split ring resonator	25
3.11	Result of S_{21} 1- The ring is perpendicular to the x-axis. 2- The ring is perpendicular to x-axis but shifted by 90 degrees. 3- The ring is perpendicular to z-axis. 4- The ring is perpendicular to z-axis but shifted 90 degrees.	26
3.12	Result of S_{21} of a waveguide filled by double edge coupled split ring resonator as in position 1	26
3.13	Result of S_{21} of a waveguide filled by double edge coupled split ring resonator as in position 2	27
3.14	Result of S_{21} of a waveguide filled by double edge coupled split ring resonator as in position 3	27
3.15	Result of S_{21} of a waveguide filled by double edge coupled split ring resonator as in position 4	28
3.16	The four possible positions of broad coupled split ring resonator	28
3.17	Result of S_{21} 1- The ring is perpendicular to the x-axis. 2- The ring is perpendicular to x-axis but shifted by 90 degrees. 3- The ring is perpendicular to z-axis. 4- The ring is perpendicular to z-axis but shifted 90 degrees.	29
3.18	Result of S_{21} of a waveguide filled by double broad coupled split ring resonator as in position 1	30

3.19	Result of S_{21} of a waveguide filled by double broad coupled split ring resonator as in position 2	30
3.20	Result of S_{21} of a waveguide filled by double broad coupled split ring resonator as in position 3	30
3.21	Result of S_{21} of a waveguide filled by double broad coupled split ring resonator as in position 4	31
3.22	Result of phase (unwrapped) of S-parameter across the pass-band of waveguide filled with metamaterial based on double rings located along z-axis.	31
3.23	Result phase (unwrapped) of S-parameter across the pass-band of waveguide filled with metamaterial based on double rings located perpendicular to z-axis.	32
4.1	(a) Two separated substrate each of opposite single split ring resonator. (b) Two separated substrate each of opposite edge coupled split ring resonator.	33
4.2	Two slabs with negative permeability located in a waveguide	34
4.3	Equivalent waveguide	35
4.4	The electric field distribution versus waveguide width a, (m=2.6mm, a=12mm) and ($d_1 = d_2 = 0.37$ mm) at $f_o = 8.3$ GHz	36
4.5	The magnetic field distribution versus waveguide width a, (m=2.6mm, a=12mm) and ($d_1 = d_2 = 0.37$ mm) at $f_o = 8.3$ GHz	36
4.6	The electric field distribution versus waveguide width a, (m=2.6mm, a=12mm) and ($d_1 = d_2 = 0.37$ mm) at $f_o = 7$ GHz	37
4.7	The propagation constant β/k_o versus resonance frequency f_o	38
4.8	Single Edge coupled split ring resonator	38
4.9	Result of S_{21} for a Single Edge coupled split ring resonator	39
4.10	Waveguide loaded by two slabs of opposite rings slot	39
4.11	Result of S_{21} for a waveguide of a=35mm where $f_c < f_o$. a) The dashed line for a stop band appeared at resonance frequency $f_o = 7.8$ GHz, filled with normal BC-SRR. b) The solid line for a stop band appeared at resonance frequency $f_o = 7$ GHz, filled with the new design.	40
4.12	Result of S_{21} for a waveguide of a=12mm where $f_c > f_o$, for the two positions (a)m/a=0.5 (b)m/a=0.125	40

4.13	Result of S_{21} for a Single Edge coupled split ring resonator $f_o=8\text{GHz}$	41
4.14	Result of S_{21} for a waveguide of $a=12\text{mm}$ where $f_c > f_o$: solid line for the case of the proposed design, dotted line for the case of single slab	41
4.15	Two separated substrate each of opposite single split ring.	42
4.16	Single SRR	42
4.17	Result of S_{21} for a Single split ring resonator	42
4.18	Waveguide filled with two slabs and the ring on each slab	43
4.19	Result of S_{21} , the solid line of a waveguide filled with the new design and the dotted line with adding losses to Cu Clad and substrate with $\sigma = 2 * 10^7 \text{ s/m}$	43
4.20	Result of 3db bandwidth of the backward wave for the propose design	44
4.21	Result of 3db bandwidth of the backward wave for BC-SRR	44
4.22	Result of S_{21} for table 4.1	45
4.23	Result of S_{21} of a rectangular waveguide ($12\text{mm} \times 6\text{mm}$) at $f_o=9\text{GHz}$, $f_o < f_c$	46

LIST OF TABLES

Table No.		Page No.
2.1	Summary of Literature Review	15
4.1	The changing of (R_i , R_o , m/a) on the resonant frequency f_o	45

LIST OF ABBREVIATIONS

BC-SRR	Broadside Coupled Split Ring Resonator
DPS	Double Positive Medium
DPS	Double Negative Medium
EC-SRR	Edge-Coupled Split Ring Resonator
E.M.F	Electromotive Force
ENG	Epsilon-Negative Medium
MNG	Mu Negative Medium
NMPM	Negative Magnetic Permeability Medium
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
P.U.L	Per Unit Length
TEM	Transverse Electromagnetic Field
TE	Transverse Electric Field
TM	Transverse Magnetic Field
SRRs	Split-Ring Resonators

LIST OF SYMBOLS

ϵ	Electric Permittivity
μ	Magnetic Permeability
E_y	Electric Field Intensity in Y Direction
E_y^{ext}	External Electric Field Intensity in Y Direction
β	Wave Propagation Constant in Z Direction
k_0	Free Space Propagation Constant
f_{co}	Cutoff Frequency for empty waveguide
f_c	Cutoff Frequency for totally loaded waveguide with metamaterial
f_{cp}	Cutoff frequency for partially loaded waveguide with metamaterial
f_o	Resonance Frequency
k	Propagating Constant
ω	Angular Frequency
μ_0	Permeability in Vacuum
ϵ_{eff}	Effective Dielectric Constant
ϵ_0	Dielectric Permittivity in Vacuum
ω_c	Cutoff Angular Frequency
Φ	Magnetic Flux
B	Magnetic Field Density
B_x^{ext}	External Magnetic Field Density In X Direction
m_x	Magnetic Dipole Moment In X Direction
P_y	Electric Dipole Momentum in Y Direction
μ_l	Permeability in the Longitudinal Direction
μ_{tr}	Permeability in the Transverse Direction
S_{21}	Transmission Coefficient
m_z	Magnetic Dipole in Z Direction
H_x	Magnetic Field In X Direction

Abstract

This research aims to study and analyze the electromagnetic phenomena of media with negative transverse permeability and how this leads into some physical phenomena such as the appearance of backward waves and the propagation below cutoff. This study and analysis is through the use of metamaterials of split ring resonator. The research has evidenced that the waveguide size can be miniaturize to smaller than its half. Also, the research has proved that the analytical determination of the electric and magnetic field inside the waveguide with the presence of the slab of dielectric permittivity and negative transverse permeability, and experimental Results of each case are shown clearly. Finally, it was shown how to achieve a high magnetic dipole to increase the negative transverse permeability, so that the losses can be decreased for a wider backward wave band.

Keywords

Negative transverse permeability, Metamaterials, Backward Waves, Miniaturization of Waveguide, and Propagation below cut off.