



**AIN SHAMS UNIVERSITY**  
**FACULTY OF ENGINEERING**  
**Electronics and Communications Engineering Department**

## **Metamaterials for Wireless Component Design**

### **A Thesis**

Submitted in partial fulfillment of the requirements of the degree of  
Master of Science in Electrical Engineering

Submitted by

**Ahmed Elsayed Mohamed Fouda**

B.Sc. of Electrical Engineering  
(Electronics and Communications Engineering)  
Ain Shams University, 2007

Supervised by

**Prof. Dr. Hadia Mohamed El-Hennawy**  
**Prof. Dr. Amr Mohamed Ezzat Safwat**

Cairo, 2010

## **BIOGRAPHICAL SKETCH**

**Author:** Ahmed Elsayed Fouda

**Degree:** Bachelor of Science in Electrical Engineering  
Faculty of Engineering, Ain Shams University.

**Date:** August 2007

**Place of Birth:** Cairo, Egypt

**Major:** Electronics and Communication Engineering

## **ACKNOWLEDGMENT**

In the name of Allah the most Merciful the most Gracious. I associate all praise to Allah for blessing us with what we had accomplished.

I start with thanking all my professors and tutors at Ain Shams University. I learnt a lot from them throughout my years of studying at the university. They provided us with very solid basics. I really owe them a lot.

I would like to thank in particular my thesis advisors; Prof. Hadia El-Hennawy, the dean of the faculty, for her encouragement, cooperation and help with the official documents. And my direct advisor Prof. Amr Safwat for his continuous support, true guidance, nice personality and sincere advice in different aspects of life. I thank him a lot for the time he dedicated to me and the effort he exerted in revising my paper and thesis.

I am also very grateful to Prof. Mahmoud Hanafi and Prof. Daaa Khalil. I learnt most of my basics in electromagnetics from them. I also learnt a lot from working with them as a teaching and research assistant. I would like also to thank Prof. Aladin Kamel. I was always in contact with him, he provided me with a lot of advice and help during my university application process.

I remember also to thank Prof. Hany Fikry for allowing me to use the fabrication and measurement facilities at the French University in Egypt. I owe any thanks to Mr. Magued Sabry for his great help in fabricating and measuring the structures.

Finally, I offer all my thanks and love to my mother for supporting me throughout my entire life. I would have never reached any success if it hadn't been for her continuous care and encouragement.

*Ahmed Fouda*

**Cairo, Egypt  
Summer 2009**

## ABSTRACT

In this thesis, two applications of the coupled line composite right/left-handed (CL-CRLH) unit cell, compact size rat-race hybrid and arbitrary-coupling directional coupler (DC) are presented. Benefiting from the slow-wave effect present in both the right-handed (RH) and left-handed (LH) regions of the CL-CRLH unit cell, two compact size rat-race hybrids were realized. 60% area reduction was achieved while preserving the conventional rat-race performance. The arbitrary coupling directional coupler (DC), which operates in the stopband around the balance frequency, showed excellent in-band and out-of-band performance. To reduce its size, a slow-wave CL-CRLH unit cell was proposed. The proposed unit cell achieves a 38% size reduction. The rat-race hybrids were fabricated on microstrip technology, whereas the directional couplers were fabricated on stripline technology. Simplified circuit models for the unit cells were developed. Theoretical expectations were confirmed by EM simulations and measurements.

A tunable CL-CRLH is also proposed. Simulated results showed the capability of the unit cell to be used as wide-range-load matching section and as a reconfigurable rat-race/branch-line hybrid.

**Key words:** Composite right/left-handed transmission lines, directional couplers, metamaterials, power dividers, wide-range-load matching section.

## CONTENTS

List of Tables.....	viii
List of Figures.....	ix
List of Symbols.....	xiv
List of Acronyms.....	xvii
1 Introduction.....	1
1.1 Motivation.....	1
1.2 Thesis organization.....	1
2 Metamaterials .....	3
2.1 Metamaterials and their unique properties.....	3
2.1.1 Backward wave propagation.....	5
2.1.2 Negative refractive index .....	6
2.1.3 Frequency dispersion.....	7
2.2 Difference between metatmaterials and conventional backward wave structures.....	7
2.3 CRLH TLs (1-D Metamaterials).....	10
2.3.1 Theory and analysis.....	10
2.3.2 Balance condition.....	18
2.3.3 PRH TL .....	19
2.3.4 PLH TL.....	21
2.3.5 Propagation constant and characteristic impedance evaluation.....	22
2.3.6 Implementation techniques.....	27
2.3.7 Radiation properties .....	31
2.4 Applications.....	33

2.4.1 Guided wave applications.....	33
2.4.2 Radiated wave applications.....	35
2.5 2-D metamaterials.....	36
3 Coupled line CRLH TL .....	41
3.1 CL-CRLH unit cell.....	41
3.1.1 Complex propagation constant and Bloch impedance.....	43
3.1.2 Balance condition.....	46
3.2 CL-CRLH unit cell advantages.....	47
4 Applications of the Coupled line CRLH unit cell: Compact Rat-Race Hybrid.....	49
4.1 Conventional rat-race hybrid.....	49
4.2 CL-CRLH unit cell design.....	51
4.2.1 RH cells.....	52
4.2.2 LH cell .....	52
4.3 Compact rat-race hybrid: RH design.....	54
4.4 Compact rat-race hybrid: LH design.....	57
4.5 Comparison with the conventional design.....	60
5 Applications of the Coupled line CRLH unit cell: Arbitrary Coupling DC.....	63
5.1 Coupled line theory.....	63
5.1.1 Impedance couplers.....	63
5.1.2 Phase couplers.....	69
5.2 Theory of CRLH couplers.....	71
5.3 Applications of CRLH couplers.....	77
5.4 Coupled CL-CRLH unit cell design.....	78

5.5 Arbitrary Coupling DC performance.....	85
5.6 Slow wave CL Compact Cell.....	88
5.7 Compact Arbitrary Coupling DC performance.....	91
6 Tunable Coupled lines CRLH TL and applications.....	94
6.1 Tunable CL-CRLH unit cell.....	94
6.2 Arbitrary load matching section .....	98
6.3 Reconfigurable Branch-line/Rat-Race hybrids.....	103
7 Conclusions and future work .....	110
7.1 Conclusion .....	110
7.2 Future work .....	110
7.2.1 2-D CL-CRLH TL.....	110
7.2.2 Slotted line cell.....	112
7.2.3 Leaky wave antenna.....	113
References .....	116



## List of Tables

2.1	CRLH TL performance if $\omega_{se} < \omega_{sh}$	16
2.2	CRLH TL performance if $\omega_{se} > \omega_{sh}$	17
4.1	Comparison between the proposed compact rat-race hybrids and the conventional one	62
6.1	Matching section parameters for different load impedances.	100
6.2	Reconfigurable hybrid parameters for rat-race operation.	106
6.3	Reconfigurable hybrid parameters for branch-line operation.	108

## List of Figures

2.1	Four materials classes according to their constitutive parameters	4
2.2	Comparison between natural materials and artificially engineered materials. (a) Natural materials crystal lattice. (b) Artificial material formed by periodic cells.	5
2.3	Wave vector and Poynting vector triads. (a) RH triad. (b) LH triad.	6
2.4	Flat lens focusing based on the negative index of refraction property of metamaterials.	7
2.5	Comparison between wave propagation in Bragg diffraction structures and LH materials. (a) Bragg diffraction structures. (b) LH materials.	9
2.6	CRLH TL unit cell.	10
2.7	Complex propagation constant of unbalanced CRLH TL.	13
2.8	Normalized characteristic impedance of unbalanced CRLH TL.	13
2.9	Group and phase velocities of unbalanced CRLH TL.	14
2.10	Normalized series and shunt branch impedances.	15
2.11	Dispersion relation of balanced CRLH TL.	18
2.12	Balanced CRLH TL unit cell.	19
2.13	PRH TL unit cell.	20
2.14	PRH TL dispersion relation.	20
2.15	PLH TL unit cell.	21
2.16	PLH TL dispersion relation.	22
2.17	Voltages and currents across the terminals of a unit cell in an infinite periodic structure.	24

2.18	Lumped surface mount components unit cell.	28
2.19	Interdigital capacitor and stub inductor TL and unit cell.	29
2.20	Mushroom cell TL.	30
2.21	Split Ring Resonator and equivalent circuit. (a) Double Split Ring. (b) Single Split Ring.	30
2.22	Guidance and radiation regions of CRLH TLs.	32
2.23	Longitudinal and transverse propagation constants of radiation mode propagating along the x-direction.	32
2.24	CRLH resonator. (a) Dispersion relation. (b) Field distribution.	34
2.25	Schematic of a leaky-wave antenna.	35
2.26	TL model of 2-D CRLH TL.	36
2.27	Mushroom cell implementation of 2-D CRLH TL.	37
2.28	2-D CRLH TL using Split Ring Resonators	37
2.29	A photo of planar lens	38
2.30	2-D flat lens ray traces.	38
2.31	3-D cubic unit cell proposed by Kron.	39
3.1	CL-CRLH unit cell schematic	41
3.2	Equivalent circuit model	41
3.3	Unit cell performance dashed-line: dispersion relation and solid line: Bloch impedance	44
3.4	Simplified equivalent circuit model near LH to RH transitions.	45
4.1	Conventional rat-race hybrid schematic.	50
4.2	Conventional rat-race hybrid circuit model.	51

4.3	RH cell performance. Dashed line: phase shift. Solid line: Bloch impedance	53
4.4	LH cell performance. Dashed line: phase shift. Solid line: Bloch impedance	53
4.5	Compact rat-race hybrid: RH design	54
4.6	Compact RH rat-race S-parameters. (a) $S_{21}$ and $S_{31}$ , measurements versus EM simulations. (b) $S_{11}$ and $S_{41}$ , measurements versus EM simulations	56
4.7	Compact RH rat-race phase response	57
4.8	Compact rat-race hybrid: LH design	58
4.9	Compact RH rat-race S-parameters. (a) $S_{21}$ and $S_{31}$ , measurements versus EM simulations. (b) $S_{11}$ and $S_{41}$ , measurements versus EM simulations.	59
4.10	Compact LH rat-race phase response	60
4.11	Compact and conventional rat-race S-parameters	61
5.1	Symmetric edge coupled coupler schematic	64
5.2	Coupled lines modes. (a) Even mode field configuration and equivalent circuit model. (b) Odd mode field configuration and equivalent circuit model	65
5.3	TL model of the CRLH coupler and the even and odd modes the equivalent models.	72
5.4	S-parameters of the CRLH coupler. (a) Even mode. (b) Odd mode	75
5.5	Even and odd modes characteristic impedance and the matching condition to $70\Omega$ line	77
5.6	Add/drop multiplexer schematic	78
5.7	Coupled CL-CRLH unit cell schematic	79

5.8	Coupled CL-CRLH cell even mode performance dashed-line: dispersion relation and solid line: Bloch impedance	83
5.9	Coupled CL-CRLH cell odd mode performance dashed-line: dispersion relation and solid line: Bloch impedance	84
5.10	Coupled CL-CRLH cell .Imaginary parts of $Z_{B,e}$ and $Z_{B,o}$ , and the input impedance	84
5.11	Arbitrary coupling directional coupler (DC) (a) A photograph of the fabricated five cells DC printed on the lower substrate (b) A photograph of the lower and the upper substrates bound together to construct a stripline structure	86
5.12	Arbitrary coupling DC S-parameters. (a) $S_{21}$ and $S_{31}$ , measurements versus EM simulations. (b) $S_{11}$ and $S_{41}$ , measurements versus EM simulations	87
5.13	Slow-wave coupled CL-CRLH cell schematic	89
5.14	Slow-wave coupled CL-CRLH cell even mode performance dashed-line: dispersion relation and solid line: Bloch impedance	89
5.15	Slow-wave coupled CL-CRLH cell odd mode performance dashed-line: dispersion relation and solid line: Bloch impedance	90
5.16	Slow-wave coupled CL-CRLH cell. Imaginary parts of $Z_{B,e}$ and $Z_{B,o}$ , and the input impedance	91
5.17	A photograph of the fabricated five cells compact DC printed on the lower substrate	92

5.18	Slow-wave compact DC S-parameters. (a) $S_{21}$ and $S_{31}$ , measurements versus EM simulations. (b) $S_{11}$ and $S_{41}$ , measurements versus EM simulations	93
6.1	Tunable unit cell layout	95
6.2	Tunable cell circuit schematic	96
6.3	Tunable cell equivalent circuit model	97
6.4	Complex load regions that can be matched by the CRLH line. (a) Case A. (b) Case B.	99
6.5	Example 1 complex propagation constant and Bloch impedance	101
6.6	Example 1 S-parameters	101
6.7	Example 2 complex propagation constant and Bloch impedance	102
6.8	Example 2 S-parameters	102
6.9	Conventional branch-line hybrid schematic.	103
6.10	Conventional branch-line hybrid circuit model.	104
6.11	Reconfigurable rat-race/branch-line hybrid circuit schematic	105
6.12	Rat-race operation S-parameters. (a) Magnitudes response. (b) Phase response	107
6.13	Branch-line operation S-parameters. (a) Magnitudes response. (b) Phase response.	109
7.1	Proposed 2-D CL-CRLH TLs. (a) Design (a). (b) Design (b).	111
7.2	Proposed slotted-line cell	112
7.3	Proposed slotted-line cell complex propagation constant and Bloch impedance	113

7.4	Proposed slotted-line leaky-wave antenna.	114
7.5	Proposed microstrip tunable leaky-wave antenna	115