



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
ELECTRONICS ENGINEERING AND ELECTRICAL COMMUNICATION

EBG-based Wideband Antenna Arrays

A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of
Philosophy in the Electrical Engineering

Submitted by

Eng. Mohamed Ismail Mohamed Ahmed

M.Sc. of Electrical Engineering

Supervised by

Prof. Dr. Esmat Abdel-Fattah Abdallah

Professor-Microstrip Department

Electronics Research Institute

Prof. Dr. Hadia Mohamed Said El-Hennawy

Former Dean - Faculty of Engineering

Ain Shams University

Cairo, Egypt

2015



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
CAIRO-EGYPT

Examiners Committee

Name: Mohamed Ismail Mohamed Ahmed

Thesis: EBG-based Wideband Antenna Arrays

Degree: Doctor of Philosophy in Department of Electronics and
Communication Engineering.

Name, Title and Affiliation		Signature
1	Prof. Dr. Ibrahim A. Salem Former President of Military Technical College.
2	Prof. Dr. Abdelhalim A. Zekry Professor in Electronics and Communication Engineering Dept., Ain Shams University.
3	Prof. Esmat Abdel-Fattah Abdallah Former President of Electronics Research Institute and Professor in Microstrip Dept.
4	Prof. Hadia Mohamed Said El Hennawy Former Dean of Faculty of Engineering, Ain Shams University and Professor in Electronics and Communication Engineering Dept.

Date: 5 / 9 / 2015

Date: 5 / 9 / 2015



ACKNOWLEDGEMENTS

All gratitude is due to “*ALLAH*” who guides me to bring forth to light this thesis.

Pursuing Ph.D. in EBG-based Wideband Antenna Arrays is one of the most valuable and exciting experiences in my education. The knowledge I learned and confidence I gained during the studying years will be beneficial to my whole life.

I owe my deepest gratitude to my supervisor, Prof. Dr. Esmat A. Abdallah, *Former President of Electronics Research Institute*, whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject. Prof. Dr. Esmat teaches me how to be a researcher, how to be patient and how to deal with research problems quietly. Prof. Dr. Esmat exerts extreme efforts in revising thesis and papers, never forgetting any details. As a matter of fact, this thesis would not have been possible without her deeply insight, opinions and her widely knowledge (God bless her).

I also want to thank Prof. Dr. Hadia M. S. Elhennawy, Former Dean of Ain Shams University, Egypt for her interest in microwave components, her guidance in Ph.D. qualification courses, and her help in antenna radiation pattern measurement (God bless her).

Also, my deepest gratitude and sincerest thanks to Prof. Abdel Razik A. Sebak for his fruitful guidance during my scientific mission in King Saud University–Prince Sultan Advanced Tech. Research Institute, encouragement, endless help and many illuminating discussions.

Thanks for my colleagues and friends in Microstrip Department and the Electronics Research Institute staff for being around me helping and caring and in Microwave Lab, Ain Shams University for their efforts in measuring my antennas radiation patterns.

Also, I would like to thank my family. I am very grateful to my father, mother, brother and sisters who encouraged and supported me. I owe all my achievement to my wife Eng. Enas Tag Eldeen, who always encourages me for further progress, and my three kids, Habiba, Islam, and Hala, who shares all my joy and bitterness every day and night.

Curriculum Vitae

Name of the Researcher	Mohamed Ismail Mohamed Ahmed
Date of Birth	15 th of June 1976
Place of Birth	Sharkia, Egypt
Last University Degree	M.Sc in Electrical Engineering, Electrical Department, Faculty of Engineering Al-Azhar University
Date of Degree	July, 2007.

STATEMENT

This Thesis is submitted for the degree of Doctor of Philosophy to the Department of Electronics and Communication Engineering, Faculty of Engineering of Ain Shams University, 2015.

The work included in this thesis was carried out by the author in the Department of Electronics and Communication Engineering, Ain Shams University and Electronics Research Institute, Microstrip Department.

No part of this Thesis has been submitted for a degree or a qualification at any other university or institute.

Name: Mohamed Ismail Mohamed Ahmed

Signature:

Date:

Published Papers

1. M. I. Ahmed, A. A. Sebak, Esmat A. Abdallah, and Hadia M. Elhennawy, "Mutual Coupling Reduction using Defected Ground Structure (DGS) for Array Application", 15th International Symposium of Antenna Technology and Applied ElectroMagnetics (ANTEM), Toulouse, France, June 25-28, 2012.
2. M. I. Ahmed, A. A. Sebak, Esmat A. Abdallah, and Hadia M. Elhennawy, "Novel Flag Shape Microstrip Antenna Array Mutual Coupling Reduction," *Proceedings of 2nd Advanced Electromagnetics Symposium (AES)*, University of Sharjah, UAE, March 2013.
3. M. I. Ahmed, A. A. Sebak, Esmat A. Abdallah, and Hadia M. Elhennawy, "Novel KSA Sign Shape Microstrip Antenna Array Mutual Coupling Reduction," *Proceedings of 2nd Advanced Electromagnetics Symposium (AES)*, University of Sharjah, UAE, March 2013.
4. M. I. Ahmed, Esmat A. Abdallah, and Hadia M. Elhennawy, "Novel UWB Eagle Shape Slot Microstrip Antenna Array Mutual Coupling Reduction for Official Applications," *Proceedings of New Paradigms in Electronics and Information Technologies (PEIT)*, Luxor, Egypt, 30Nov. - 3 Dec., 2013
5. M. I. Ahmed, Esmat A. Abdallah, and Hadia M. Elhennawy "Design, Simulation, Fabrication, and Measurement of Antenna Array with Low Mutual Coupling for ISM Band Wireless Applications," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 3, no. 10, pp. 12275-12287, Oct. 2014.
6. M. I. Ahmed, Esmat A. Abdallah, and Hadia M. Elhennawy, "UWB KSA Sign Shape Slot Microstrip Antenna Array Mutual Coupling Reduction for Official Applications," *International Journal of Engineering and Technology*, vol. 6, no.6, pp. 513-519, 2014.
7. M. I. Ahmed, Esmat A. Abdallah, and Hadia M. Elhennawy, " Novel Wearable Eagle Shape Microstrip Antenna Array with Mutual Coupling Reduction" *Progress In Electromagnetics Research B*, vol. 62, pp. 87-103, 2015.
8. M. I. Ahmed, Esmat A. Abdallah, and Hadia M. Elhennawy, "SAR Investigation of Novel Wearable Reduced-Coupling Microstrip Antenna Array" *International Journal of Engineering and Technology-IJENS*, vol. 15, no.3, pp. 78-87, June 2015.



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
CAIRO-EGYPT

Electronics and Communications Department

Supervised by

Prof. Dr. Esmat A. Abdallah, and Prof. Dr. Hadia M. Elhennawy

SUMMARY

Printed monopole antennas are indispensable candidates for WLAN, UWB, and RFID applications. Along with the small size, the antenna should preferably be low cost, light weight, less fragile and low profile. The main aim of this thesis is design, simulation, fabrication, and measurement of wideband antenna array. The printed monopole antenna array is studied. The derived transmission line model was found for a slot antenna by two methods. First, a simple and accurate model of the offset fed transverse slot radiator is introduced. The second method is equating the delivered power to a lossy transmission line and the radiated power by a slot. From these, the total radiated power is found in terms of the radiated loss per-unit-length (α). The input impedance of printed linear slot antenna simplified derivations are presented. Next, the electric field equation and radiated power of the slot are corrected and proofread. Also, the input impedance and performance of printed monopole antenna array are discussed. The mutual coupling between the array elements is reduced using Electromagnetic Band Gap (EBG) structures. The EBG structures are divided to: Defected ground structure (DGS), mushroom-like EBG, and uni-planar EBG. All the three types are discussed.

The rapid expansion of wireless technology during the last years has drawn new demands on integrated components including also antennas. The existence of an immense infrastructure worldwide for the 2.4 GHz Industrial, Scientific and Medical (ISM) band along with the release of the 5.6 GHz ISM band, combined with its increasing popularity, related to the Bluetooth and/or WLAN systems applications. A low mutual coupling design for two and four elements microstrip antenna array are proposed. A new distribution for dumbbell shaped defect on the ground plane of the antenna is inserted between the patches creating a band gap in the operation frequency band of the antenna. By suppressing the surface waves, it provides a very low mutual

coupling between array elements. The DGS antenna is analyzed using a finite integration technique (FIT) and a mutual coupling reduction of 35.6dB is achieved. The analysis indicates that increasing number of dumbbells reduces the mutual coupling between elements. Radiation patterns have minimal change in the broadside direction but back lobe level is increased. However, the gain and the efficiency are decreased due to penetration of DGS in the ground plane. The results agree with those obtained by the full wave simulator method. It is noticed that the ground plane penetration is the DGS main problem.

One of the dominant research topics in antennas for body-centric communications is the wearable, and the fabric-based antennas. Commonly, wearable antennas for all modern applications require light weight, low cost, almost maintenance-free and no installation. There are number of specialized occupation segments that utilize body centric communication systems, such as paramedics, fire fighters, and military. Besides, wearable antennas also can be applied for youngsters, the aged, and athletes for the purpose of monitoring. A new concept of a wearable antenna is easily integrated into clothing. A novel eagle shape and KSA slogan microstrip antenna are presented. The single- and two-element antenna array are designed and fabricated on a substrate with dielectric constant of 2.2, thickness of 1.5748 mm, and $\tan \delta = 0.001$. The microstrip array was studied by CST simulator and fabricated by proto laser machine with precision 25 μ m. The antenna can be used in the official or RFID applications. Also, this antenna may be used in soldier belts, any commodity for the official application, etc. The novel EBG cells in the shape of small size eagles and KSA slogan are inserted between the adjacent coupled elements in the array to suppress the pronounced surface waves. A mutual coupling reduction of 36 dB is achieved at first band (1.68 - 2.65) GHz and 22.1 dB at second band (6.5 – 8.86) GHz for a novel eagle shape antenna array. Also, a mutual coupling reduction of 11.9 dB is achieved at 2.542 GHz for a novel KSA slogan. The measured results agree well with those obtained by the CST. SAR calculation was carried out to measure the effect of those antennas on Human bodies. Maximum SAR of eagle shape antennas result is 1.95 W/Kg, while, maximum SAR of KSA slogan antennas result is 1.64 W/Kg that are acceptable to the IEEE C95.1: 2005 and the ICNIRP standards.

A novel UWB Eagle shape and KSA slogan shape slot microstrip antenna are presented. The single and two element antennas were designed and fabricated on a substrate with dielectric constant of 4.4, thickness of 1.6 mm, and $\tan \delta = 0.02$. The microstrip array was simulated and fabricated. A reduction in mutual coupling of 6 dB is achieved in the Eagle shape at first band (1.71 - 2.98) GHz, 10 dB at second band (4.26 – 5.62) GHz, and 6 dB at third band (6.57 – 9.16) GHz. A reduction in mutual coupling of 3 dB is achieved in the KSA slogan shape at first band (2.1 - 2.99) GHz and 33 dB at second band (4.92 – 6.73) GHz, and 7 dB at third band (6.73 – 9.28) GHz. The measured results agree well with those obtained by the CST. The antennas can be used in the military or RFID applications. These configurations are chosen because the eagle shape and KSA sign shape are the official badges for any military application. The antennas is an excellent candidate for use as internal elements in modern laptop computers. The antennas is tested among three opening angles. The EBG cells in the shape of small size

eagles and KSA slogan shape are inserted between the adjacent coupled elements in the array to suppress the pronounced surface waves.

Finally, for future work, it is desired to implement these designs in MIMO system to achieve overall better performance.

Table of Contents

Content	Pages
Cover page.....	i
Examiners Committee.....	ii
Acknowledgements	iii
Curriculum Vitae.....	iv
Statement	v
Published Papers	vi
Summary.....	vii
Table of Contents.....	x
List of Abbreviations.....	xv
List of Symbols.....	xvi
List of Figures.....	xvii
List of Tables.....	xxxiii
Chapter 1	
Introduction	1
1.1 Motivation of the Thesis	1
1.2 Thesis Objectives	2
1.3 Microstrip Antenna Array Applications in Modern Commercial Systems	2
1.4 Software Packages Used	4
1.5 Achievements and Organization of the Thesis	5
Chapter 2	
Wideband Antenna Array and Decoupling Methods, A Review	8
2.1 Introduction	8
2.2 Microstrip Patch Antenna Array Historical Background	8
2.3 Wideband Antenna Arrays	9
2.3.1 Broadband Circularly Polarized Slot Antenna Array Fed by Asymmetric CPW for L-Band Applications	11
2.3.2 A Novel Wideband and Compact Microstrip Grid Array Antenna	12
2.3.3 Super Directive Wideband Array of Planar Monopole Antenna with Loading Plates	13
2.3.4 A Wideband Slot-Coupled Stacked-Patch Array for Wireless Communications	15
2.3.5 Analysis and Design of Wideband Wide Scan Planar Tapered Slot Antenna Array	16
2.3.6 Wideband and Low Side lobe Slot Antenna Fed by Series-Fed Printed Array	17
2.3.7 Broadband Circularly Polarized Microstrip Antenna Array Using Sequentially Rotated Technique	19

2.3.8	24-GHz Bandwidth-Enhanced Microstrip Array Printed on a Single-Layer Electrically-Thin Substrate for Automotive Applications	20
2.3.9	Broadband Circularly Polarized Slot Antenna Array for L- and S-band Applications	21
2.3.10	Broadband High-Gain Microstrip Array Antennas for WiMAX Base Station	22
2.3.11	Design of a Wideband Dual Element Slot Loop Antenna Array with Adjustable Back-Reflector	23
2.3.12	A Wideband Circularly Polarized 2 X 2 Patch Array using a Sequential Phase Feeding Network	25
2.3.13	A Broadband Patch Antenna Array with Planar Differential L-Shaped Feeding Structures	27
2.4	Surface Wave	29
2.4.1	Dielectric Interfaces	29
2.4.2	Metal Surfaces	30
2.4.3	High-Impedance Surfaces	31
2.5	Decoupling Methods	31
2.5.1	Open-Circuit Voltage Method	32
2.5.2	S-Parameter Method	33
2.5.3	Full-Wave (Moment) Method	34
2.5.4	Element Pattern Method	34
2.5.5	Calibration Method	35
2.5.6	Decoupling by Antenna Design	35
2.5.7	Receiving Mutual Impedance Method	35
2.6	Mutual Coupling Reduction Methods	36
2.6.1	Micromachined Microstrip Patch Antenna with Controlled Mutual Coupling and Surface Waves	37
2.6.2	Mutual Coupling between Reduced Surface-Wave Microstrip Antennas	37
2.6.3	Analysis of Mutual Coupling between Cavity Backed Microstrip Patch Antennas	38
2.6.4	Mutual Coupling Reduction using Different Microstrip Patch Antennas Shapes	40
2.6.5	Mutual Coupling between Two Microstrip Patch Antennas on a Singly Curved Surface	45
2.7	Conclusion	47
Chapter 3		
Electromagnetic Band Gap (EBG) Structures, A Review		48
3.1	Introduction	48
3.2	EBG and Metamaterials	48

3.3	Methods for Identification of the EBG Properties	49
3.4	Analysis Methods for EBG Structures	51
3.4.1	Effective Medium Model with Lumped LC Elements	52
3.4.2	Transmission Line Model for Surface Waves	53
3.4.3	Transmission Line Model for Plane Waves	54
3.5	Parametric Study of a Mushroom-like EBG Structure	55
3.6	Comparison of Mushroom and Uni-planar EBG Designs	56
3.7	EBG Structures with Microstrip Antenna Array	58
3.8	Defected Ground Structure for Microstrip Antennas	64
3.8.1	Definition and Basic Geometries	65
3.8.2	Unit Cell DGS	65
3.8.3	Periodic DGS	69
3.8.4	Modeling of DGS	70
3.8.5	Ring-Shaped DGS for Circular Patch Array	74
3.8.6	Dumbbell-Shaped DGS for Rectangular Patch Array	75
3.8.7	Elimination of Scan Blindness of Microstrip Phased Array	76
3.12	Conclusion	77
Chapter 4		
	Analysis of Printed Monopole Antenna Array	79
4.1	Introduction	79
4.2	Axelrod et al. Method for Slot Antenna Input Impedance	80
4.3	Himdi and Daniel Method	82
4.4	Derivation of Electric Field Equation for the Rectangular Slot	85
4.5	Derivation of Radiated Power	86
4.6	Monopole Input Impedance	91
4.7	Printed Monopole Antenna Array	95
4.8	Conclusion	97
Chapter 5		
	Design, Simulation, Fabrication, and Measurement of Antenna Array for ISM Band Wireless Applications	98
5.1	Introduction	98
5.2	Single Element	98
5.3	Two Elements Array	100
5.4	E-plane Configuration Linear Four Elements Array	105
5.5	H-plane Configuration Linear Four Elements Array	108
5.6	E-plane Configuration Planar Four Elements Array	111
5.7	H-plane Configuration Planar Four Elements Array	114
5.8	Experimental Results And Discussion	117
5.9	Conclusions	119
Chapter 6		
	Novel Shapes Wearable Microstrip Antenna Array with Mutual Coupling Reduction	120
6.1	Introduction	120
6.2	Novel Eagle Shape Antenna Design and Simulation	121
6.2.1	Single Element	121

6.2.2	Two Elements Array without EBG	124
6.2.3	Two Elements Array with EBG	126
6.3	Experimental Results and Discussion	129
6.3.1	Single Element	130
6.3.2	Two Elements Array without EBG	131
6.3.3	Two Elements Array with EBG	133
6.4	SAR Calculation	134
6.4.1	Single Element	134
6.4.2	Array without EBG	136
6.4.3	Array with EBG Cells	137
6.5	Novel KSA Slogan Shape Antenna Design and Simulations	138
6.5.1	Single Element	138
6.5.2	Two Elements Array without EBG	141
6.5.3	Two Elements Array with EBG	143
6.6	Experimental Results and Discussion	146
6.6.1	Single Element	146
6.6.2	Two Elements Array without EBG	147
6.6.3	Two Elements Array with EBG	148
6.7	SAR Calculation	149
6.7.1	Single Element	149
6.7.2	Array without EBG	150
6.7.3	Array with EBG Cells	151
6.8	Conclusion	151
Chapter 7		
Novel Shapes UWB Slotted Microstrip Antenna Array with Mutual Coupling Reduction for Laptop Computer Applications		153
7.1	Introduction	153
7.2	Novel UWB Eagle Shape Slot Microstrip Antenna Array with Reduced Mutual Coupling for Official Applications	153
7.2.1	UWB Single Element	154
7.2.2	Two Elements Array without EBG	155
7.2.3	Two Elements Array with EBG	157
7.3	Experimental Results and Discussion	161
7.3.1	Single Element	161
7.3.2	Two Elements Array without EBG	163
7.3.3	Two Elements Array with EBG	165
7.4	Embedded Antennas in Laptop Computer	167
7.4.1	Single Element	167
7.4.2	Two Elements Array without EBG	172
7.4.3	Two Elements Array with EBG	176
7.5	Mutual Coupling Reduction for Official Applications of UWB KSA Slogan Shape Slot Microstrip Antenna Array	179

7.5.1	UWB Single Element	180
7.5.2	Two Elements Array without EBG	181
7.5.3	Two Elements Array with EBG	183
7.6	Experimental Results and Discussion	187
7.6.1	Single Element	188
7.6.2	Two Elements Array without EBG	190
7.6.3	Two Elements Array with EBG	192
7.7	Embedded Antennas in Laptop Computer	194
7.7.1	Single Element	194
7.7.2	Two Elements Array without EBG	198
7.7.3	Two Elements Array with EBG	201
7.8	Conclusion	205
Chapter 8		
Conclusions and Suggestions of Future Work		206
8.1	Conclusions	206
8.2	Suggestions for Future Work	208
	Appendix (A)	209
	Appendix (B)	212
	References	213

List of Abbreviations

ADS	Advanced Design System
BPF	Band Pass Filter
BSF	Band Stop Filter
CPW	Coplanar Waveguide
CST	Computer Simulation Technology
DGS	Defected Ground Structure
EBG	Electromagnetic Bandgap Structure
EM	Electromagnetic
FIM	Finite Integral Method
FIT	Finite Integral Technique
GPS	Global Positioning System
GSM	Global System for Mobile
GUI	Graphical User Interface
IC	Integrated Circuits
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
LMDS	Local Multipoint Distribution Systems
LPF	Low Pass Filter
LTE	Long Term Evolutions
MCC	Mutual Coupling Compensation
MEMS	Micro Electro Mechanical Systems
MLS	Microwave Landing System
MMDS	Multipoint Multichannel Distribution Systems
MMIC	Monolithic Microwave Integrated Circuits
MoM	Method-of-Moments
NFC	Near Field Communication
PBG	Photonic Band Gap
PCB	Printed Circuit Board
PCS	Personal Communication System
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuits
TV	Television
UMTS	Universal Mobile Telecommunications System
UWB	Ultra-Wide-Bandwidth
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
Wi-Fi	Wireless Fidelity
Wi-MAX	Worldwide Interoperability For Microwave Access
WLAN	Wireless Local Area Network