

Contents

<i>Preface</i>	iii
<i>Acknowledgements</i>	vi
1. Metamaterial and Sensing	1
1.1 Introduction	1
1.2 Concept of metamaterial & microwave sensing	4
1.3 Metamaterial based microwave sensor design Principle: resonator structure	5
1.4 Geometry design, fabrication and performances	7
1.5 Measurement method for metamaterial properties assessment	11
1.6 Metamaterial based microwave sensor design Principle: sandwich structure	12
1.7 Unit cell design with circuit modelling and performance	12
1.8 Sensitivity performance with absorption and polarization affects	14
1.9 Stacked DNG metamaterial for biosensing	16
1.10 Stacked DNG MTM scattering parameters and dielectric characteristics	18
1.11 Blood glutamate concentration sensing performance of the MTM unit cell	21
1.12 Summary	24
2. Liquid and Solid Material Sensing Using Metamaterial	26
2.1 Introduction	26
2.2 Metamaterials and microwave sensing	28
2.3 Importance of metamaterial sensor	29
2.4 Tri Circle SRR (TCSRR) shape metamaterial sensor design and analysis	30
2.5 Electric field and surface current distribution investigation	31
2.6 Double negative (DNG) metamaterial characteristics investigation	33
2.7 Parametric study	34
2.8 Mathematical modelling of the TCSRR based metamaterial sensor	36

2.9	Sensing performance evaluation	39
2.9.1	Dielectric constant investigation of oil samples	39
2.9.2	Loss tangent analysis of oil samples	41
2.9.3	Detection and evaluation of different LUTS using TCSR structure	42
2.10	Design and analysis of complementary square SRR-based metamaterial	45
2.11	Effective parameters extraction methods	47
2.11.1	Metamaterial characteristics of the designed unit cell	48
2.11.2	Surface current, E-field, and H-field analysis	49
2.12	Equivalent circuit analysis	51
2.13	Parametric analysis	52
2.13.1	Effect of change of split gap	52
2.13.2	Effect of change of resonator width	53
2.13.3	Effect of change of substrate material	54
2.13.4	Metamaterial structure fabrication and experimental results analysis	55
2.13.5	Effective medium ratio (EMR) analysis	57
2.14	Materials and thickness sensing using the proposed sensor	57
2.14.1	Quality factor and sensitivity analysis	61
2.15	Summary	61
3.	Metamaterial for Future Generation Wireless Communications	65
3.1	Introduction	65
3.2	Metamaterial's background	67
3.3	Metamaterial based mm-wave	69
3.4	Metamaterial particle design	70
3.4.1	Principle of metamaterial working	72
3.4.2	Metamaterial properties extraction	73
3.5	Metamaterial based Sub 6 GHz	74
3.5.1	Metamaterial example	75
3.6	Analysis, design and simulation of 5G metamaterial	79
3.7	Emerging metamaterial applications	83
3.7.1	Antennas - gain improving	83
3.7.2	Miniaturizing of the size of antennas	84
3.7.3	Antenna's bandwidth enhancement	85
3.7.4	Metamaterials for multiband generation	86
3.7.5	Metasurface	86
3.8	Summary of existing research related to DNG metamaterial	87
3.9	Summary	90
4.	Metamaterial Structure Exploration for Wireless Communications	93
4.1	Introduction	93
4.2	Metamaterial with asymmetrical resonator	95

4.3	Metamaterial with single axis symmetric resonator with applications	97
4.3.1	Design of MTM unit cell	97
4.3.2	Result analysis of the metamaterial	98
4.3.3	Application of metamaterial in antenna for performance enhancement	98
4.3.4	Application of the metamaterial as an absorber	101
4.4	Two axes symmetric metamaterial and it's application	102
4.4.1	MTM design and result analysis	102
4.4.2	Antenna gain enhancement using MTM superstrate	104
4.5	Mirror symmetric resonator based tuned metamaterial	105
4.5.1	Design of the metamaterial	105
4.5.2	Frequency tuning of the metamaterial	107
4.6	Rotating symmetric resonator based metamaterial absorber	108
4.6.1	Metamaterial absorber (MMA) design	108
4.6.2	Frequency tuning of the MMA	110
4.6.3	Metamaterial property analysis of the MMA	112
4.6.4	Power and current distribution analysis of MMA	113
4.6.5	Angular stability and polarization insensitivity study of MMA	116
4.6.6	Experimental result of the MMA	117
4.7	Summary	119
5.	Metamaterial Antennas for Ultra-wideband Applications	123
5.1	Introduction	123
5.2	Metamaterial and UWB antennas	125
5.2.1	Metamaterials	125
5.2.2	Ultra wideband (UWB) technology	127
5.3	Metamaterial based antenna design	130
5.3.1	Unit cell configuration	130
5.3.2	Antenna geometry	133
5.3.3	Experimental validation	135
5.3.4	Surface current distribution	135
5.3.5	Time domain performance	136
5.4	Summary	139
6.	Flexible Metamaterials for Microwave Application	142
6.1	Introduction	142
6.2	Importance of flexible substrate materials for microwave application	144
6.3	Development of flexible substrate material	146
6.3.1	Synthesis of $Mg_xZn_{(1-x)}Fe_2O_4$ nanoparticles	147
6.4	Characterization of $Mg_xZn_{(1-x)}Fe_2O_4$ nanoparticles	148
6.4.1	Structural analysis	148
6.4.2	Morphological analysis	151
6.4.3	Dielectric properties analysis	153

6.4.4	Optical and photoluminescence analysis	155
6.4.5	Magnetic properties analysis	156
6.5	Flexible metamaterial design technique	158
6.5.1	Metamaterials on $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ nanoparticles-based flexible substrate	158
6.5.2	Metamaterial measurement method	161
6.5.3	Performance of flexible metamaterial with $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ nanoparticles with Mg_{40}	163
6.5.4	Electromagnetic properties analysis of the flexible metamaterial with Mg_{40}	165
6.5.5	Electromagnetic field interaction of the metamaterial properties with Mg_{40}	167
6.5.6	Performance analysis of flexible metamaterial-properties with Mg_{60}	168
6.5.7	Comparison of $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ nanoparticles-based proposed flexible metamaterials with Mg_{40} and Mg_{60}	170
6.5.8	Comparison of $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ nanoparticles-based proposed flexible metamaterials with existing metamaterials	170
6.6	Summary	171
7.	Microwave Head Imaging and 3D Metamaterial-inspired Antenna	175
7.1	Introduction	175
7.2	CCSRR based metamaterial structure design	178
7.2.1	Design and analysis of CCSRR unit cell structure	178
7.2.2	Effective medium parameters of CCSRR unit cell	179
7.2.3	Equivalent circuit model of CCSRR unit cell structure	181
7.2.4	Parametric study of CCSRR unit cell structure	183
7.2.5	Design and analysis of CCSRR loaded 3D antenna	184
7.2.6	Mathematical modeling of the CCSRR loaded 3D antenna	185
7.2.7	Parametric study of CCSRR loaded 3D antenna	188
7.2.8	Antenna fabrication and measurement	189
7.2.9	Head phantom fabrication and measurements	190
7.2.10	Preparation and fabrication of tissue mimicking head phantom	190
7.2.11	Electrical properties measurement technique	193
7.3	EM head imaging system	194
7.3.1	Imaging setup with nine antennas	194
7.3.2	Antenna phase center optimization	195
7.4	Image reconstruction technique	196
7.4.1	IC-CF-DMAS image reconstruction algorithm	196
7.4.2	Matching medium consideration	198
7.4.3	Internet of things framework for em head imaging system	199
7.5	CCSRR loaded 3D antenna with head model	200
7.5.1	Specific absorption rate (SAR) analysis	204

7.5.2	SAR analysis of CCSRR loaded 3D antenna	204
7.5.3	Measurements of CCSRR loaded 3D antenna fabricated prototype	205
7.6	Electrical properties of tissue mimicking head phantom	208
7.7	Em imaging results	209
7.7.1	Imaging results with CCSRR loaded 3D antenna setup	212
7.8	Sensitivity analysis	214
7.8.1	Internet of things based image transfer	215
7.9	Summary	216
8.	Metamaterial Inspired Stacked Antenna Based Microwave Brain Imaging	221
8.1	Introduction	221
8.2	Importance of deep learning in current brain imaging technologies	224
8.3	Metamaterial loaded stacked antenna	225
8.3.1	Stacked antenna structure design and analysis	225
8.3.2	Stacked antenna geometry and design evolution analysis	226
8.3.3	Parametric analysis of MTM loaded stacked antenna	230
8.4	Stacked antenna prototype fabrication and performance analysis	231
8.5	Radiation characteristic analysis of the stacked antenna	233
8.6	Performance analysis of the stacked antenna with head model	236
8.7	Specific absorption rate (SAR) analysis of stacked antenna	239
8.8	Microwave brain imaging (MBI) system implementation method	240
8.9	Image data collection pre-processing and augmentation techniques	242
8.9.1	Image data collection	245
8.9.2	Image pre-processing and input size requirement	245
8.9.3	Image augmentation technique	245
8.10	Deep learning based tumor segmentation and classification models	246
8.11	Microwave segmentation network (MSegNet)-brain tumor segmentation model	247
8.11.1	Architecture of MSegNet segmentation model	247
8.11.2	Training experiment of MSegNet model	250
8.11.3	Evaluation matrix for the MSegNet segmentation model	251
8.11.4	Brain tumor segmentation performances	252
8.12	BrainImageNet (BINet)-brain tumor classification model	253
8.12.1	Mathematical analysis of the classification model	253
8.13	Architecture of BINet classification model	254
8.14	Training experiment of BINet classification model	255
8.15	Evaluation matrix for the BINet classification model	256
8.16	Brain images classification performances of the BINet model	257
8.17	Receiver operating characteristic of BINet model	258
8.18	Miss classification performance analysis of BINet model	259
8.19	Summary	260

9. Lower UHF Metamaterial Antenna for Nanosatellite Communication System	263
9.1 Introduction	263
9.2 Antennas for nanosatellite	265
9.3 EMNZ metamaterial design and characterization	267
9.4 EMNZ inspired UHF antenna	270
9.5 Summary	276
<i>Index</i>	279